Life Cycle Assessment of biochar, electricity, and heat from a wood gasification plant

Master Thesis

Submitted in Fulfillment of the Degree
Master of Science in Engineering (MSc.)

University of Applied Sciences Vorarlberg
Energy techniques and energy economics

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Dornbirn, 10.09.2021

Abstract

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In recent years, numerous studies around the world have examined the environmental potential of biochar to determine whether it can help address climate challenges. Several of these studies have used the Life Cycle Assessment (LCA) method to evaluate the environmental impacts of biochar systems. However, studies focus mainly on biochar obtained from pyrolysis, while the number of studies on biochar from gasification is small.

To contribute to the current state of LCA research on biochar from gasification, LCA was performed for biochar, electricity, and heat from a wood gasification plant in Vorarlberg, Austria. Woodchips from local woods are used as biomass feedstock to produce energy, i.e., electricity and heat. Thereby, biochar is obtained as a side product from gasification. The production of syngas and biochar takes place in a floating fixed-bed gasifier. Eventually, the syngas is converted to electricity in a gas engine and fed to the power grid. Throughout different stages within the gasification process, heat is obtained and fed into local heat grid to be delivered to customers. The biochar produced complies with the European Biochar Industry (EBI) guidelines and is used on a nearby farm for manure treatment and eventually for soil application. Thereby, the effect of biochar used for manure treatment is considered to reduce emissions occurring from manure, i.e., nitrogen monoxide (N_2O). Further, the CO_2 sequestration potential of biochar, i.e., removal of CO_2 from the atmosphere and long-term storage, is considered. Several constructions, such as the construction of the gasification system and the heating grid, are included in the evaluation.

As input related reference flow, 1 kg of woodchips with water content of 40 % is used. Three functionals units are eventually obtained, i.e., 0.17 kg of biochar applied to soil, 4.47 MJ of heat and 2.82 MJ of electricity, each per reference flow. The results for Global Warming Potential (GWP) for biochar is – 274.7*10 $^{-3}$ kg CO_{2eq} per functional unit, which corresponds to – 1.6 kg CO_{2eq} per 1 kg biochar applied to soil. The GWP for heat results in 17.1*10 $^{-3}$ CO_{2eq} per functional unit, which corresponds to 3.6*10 $^{-3}$ kg CO_{2eq} per 1 MJ. For electricity, a GWP of 38.1*10 $^{-3}$ kg CO_{2eq} per functional unit is obtained, which is equivalent to 13.5*10 $^{-3}$ kg CO_{2eq} per 1 MJ.

The calculation was performed using SimaPro Version 9.1 and the ReCiPe method with hierarchist perspective.

Kurzreferat

Lebenszyklusanalyse von Biokohle, Strom und Wärme aus einer Holzvergasungsanlage

In den letzten Jahren haben zahlreiche Studien auf der ganzen Welt das Umweltpotenzial von Biokohle untersucht, um festzustellen, ob sie zur Bewältigung der klimatischen Herausforderungen beitragen kann. In mehreren dieser Studien wurde die Methode der Lebenszyklusanalyse (LCA) verwendet, um die Umweltauswirkungen der einzelnen untersuchten Biokohlesysteme zu bewerten. Diese Studien konzentrieren sich hauptsächlich auf durch Pyrolyse gewonnene Biokohle, während die Anzahl der Studien über Biokohle aus Vergasungsprozessen vergleichsweise gering ist.

Um einen Beitrag zum aktuellen Stand der LCA-Forschung über Biokohle aus Vergasungsprozessen zu leisten, wurde eine LCA für Biokohle, Strom und Wärme aus einer Holzvergasungsanlage in Vorarlberg, Österreich, erstellt. Holzhackschnitzel aus heimischen Wäldern werden als Biomasse-Rohstoff verwendet, um Energie in Form von Elektrizität und Wärme zu erzeugen. Während des Vergasungsprozesses fällt Biokohle als Nebenprodukt an. Synthesegas und Biokohle werden in einem Schwebefestbettvergaser erzeugt, die Umwandlung in Strom erfolgt schließlich in einem Gasmotor. Der erzeugte Strom wird in das Stromnetz eingespeist. In verschiedenen Phasen des Vergasungsprozesses wird Wärme gewonnen, die schließlich in das örtliche Wärmenetz eingespeist und an die Kunden geliefert wird. Die erzeugte Biokohle entspricht den Richtlinien der Europäischen Biokohleindustrie (EBI) und wird in einem nahen gelegenen landwirtschaftlichen Betrieb zur Güllebehandlung und schließlich zur Ausbringung auf den Boden verwendet. Dabei wird davon ausgegangen, dass die für die Güllebehandlung verwendete Biokohle zu einer Verringerung der Emissionen von Stickstoffmonoxid (N_2O) aus Gülle führt. Außerdem wird das CO_2-Sequestrierungspotenzial von Biokohle, d. h. die Bindung von CO_2 aus der Atmosphäre und dessen langfristige Speicherung, berücksichtigt. Mehrere Konstruktionen, wie der Bau der Vergasungsanlage und des Wärmenetzes, werden in die Bewertung einbezogen.

Als inputbezogener Referenzstrom wird 1 kg Holzhackschnitzel mit einem Wassergehalt von 40 % verwendet. Als Berechnungstool wurde die LCA-Software SimaPro Version 9.1 und die ReCiPe-Methode mit hierarchischer Sichtweise verwendet.

Die Berechnungen ergeben schließlich drei funktionelle Einheiten: 0,17 kg auf den Boden ausgebrachte Biokohle, 4,47 MJ Wärme und 2,82 MJ Strom, jeweils pro Referenzfluss. Das Ergebnis hinsichtlich des Treibhauspotentials (GWP) für Biokohle ist - 274,7*10^{-3} kg CO_{2eq} pro funktionelle Einheit, dies entspricht - 1,6 kg CO_{2eq} pro 1 kg auf den Boden ausgebrachte Biokohle. Das GWP für Wärme ergibt 17,1*10^{-3} CO_{2eq} pro funktionelle Einheit, dies entspricht 3,6*10^{-3} kg CO_{2eq} pro 1 MJ. Für Strom ergibt sich ein GWP von 38,1*10^{-3} kg CO_{2eq} pro Funktionseinheit, dies entspricht 13,5*10^{-3} kg CO_{2eq} pro 1 MJ.

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1. Introduction

By introducing the European Green Deal, a political framework has been set with the intention to create a sustainable economic future for all European member states and their citizen. Milestones are set along the way, peaking in climate neutrality by 2050 and demanding efforts encompassing all sectors of the economy [1]. Strategic priorities focus on the increase of energy efficiency, decarbonization of energy supply and transportation, enhancing natural carbon sinks in agriculture and the creation of greenhouse gas (GHG) sinks by so-called negative emissions technologies (NET). A common example of a NET is the CO_2 sequestration, i.e., the active removal of CO_2 from the atmosphere and its further storage in soil to achieve a reduction of CO_2 in the atmosphere. The storage phase is thereby ideally carried out for a very long period of time [2]. According to FAWZY ET AL. [3] and AZZI ET AL. [4], biochar systems have been presented as one of the most promising and readily NET, where CO_2 removal from the atmosphere occurs naturally by means of photosynthesis while plant growth. Fixation of the carbon that was previously removed is achieved by thermochemical conversion of biomass such as pyrolysis and gasification, i.e., the production of biochar. The biochar produced is chemically stable in natural environments and resistant to biodegradation. Only further thermochemical conversion such as combustion of the biochar can undo the carbon fixation in the biochar. Thus, the application of biochar to soil prevents further thermochemical conversion, therefore creating a long-term CO_2 sink with storage potential for about hundreds up to thousands of years [3].

In addition to the potential of CO_2 sequestration, biochar has other environmental potentials that can be elementary for agriculture. For instance, there is the potential to reduce N_2O emissions, which are directly linked to the occurrence of manure and thus is directly attributable to animal husbandry. The potential becomes clear when expressed in numbers: in Austria, GHG emissions from the agricultural sector amounted to 8.1 million t CO_{2eq} in 2019, which represents 10.2 % of the country's total GHG emissions [5]. One of the main sources thereby is the emission of N_2O, which is mainly formed by the use of fertilizers and fertilizer management. With a reported potential by CAYUELA ET AL.[6] to reduce N_2O to up to 54 %, biochar can be a game changer in addressing agricultural emissions.

To pick up the current state of research in context of biochar potentials, the present work aims to evaluate the environmental impacts of biochar, heat, and electricity from a wood gasification plant in Vorarlberg, Austria by using the method of LCA. The upstream processes of biomass production, gasification, and energy production, as well as the construction of the plant and heating grid are considered. For the assessment of biochar, the amount of CO_2 sequestered and the reduction of N_2O due to manure treatment with biochar on the farm are of particular importance.

This work is a continuation of the master's thesis by KÄPPLER [7], who performed LCA for the same wood gasification plant in 2017. At that time, however, no evaluation for the actual use of biochar took place. By means of this work, the aspect of the use of biochar is taken into account. Furthermore, all processes are evaluated, detailed and updated to the year of operation 2020. The thesis starts with a short introduction on thermochemical conversion processes and biochar in chapter 2 and 3, followed by a literature research with focus on

LCAs on biochar in chapter 4. The system assessed and methods used are described in chapter 5 and 0. In chapter 7, the data used for evaluation is presented. Results of the assessment are presented in chapter 8 and a discussion of the results is provided in chapter 9.

2. Thermochemical conversion processes

Chemical energy is stored in biomass, which can be made usable as thermal energy by thermochemical conversion processes. These conversion processes can be either direct, i.e., by combustion, or indirect, initially by generating a secondary energy carrier [8]. Indirect forms of thermochemical conversion processes include pyrolysis and gasification. In both processes, the absence or presence of an oxidant, e.g., air, is a determining factor, which is expressed as excess air ratio λ. Another determining factor is the targeted product of the process. Both forms of thermochemical conversion, pyrolysis and gasification, are explained in the following.

2.1 Pyrolysis

The targeted products of pyrolysis are the secondary energy carrier pyrolysis oil and pyrolyzed charcoal and pyrolysis gas. To obtain the targeted products, biomass is heated in a first step, so that remaining water or moisture contained in the biomass is evaporated [8]. In a second step, the dried biomass is further heated in the absence of an oxidant ($\lambda \approx 0$), thereby reaching temperatures of 200 – 600 °C. The heat input required for this process thus makes pyrolysis an endothermic process. During pyrolysis reaction, the condensable part of the volatile matter forms pyrolysis oil, the remaining solids are pyrolyzed charcoal.

The shares on the yield of each solid, liquid, and gaseous products depend on the type of pyrolysis that can vary in their operating conditions, so speak in temperature, duration, and heating rate. Depending on the degree of each of these operating condition variables, it´s distinguished between, slow, fast, and flash pyrolysis.

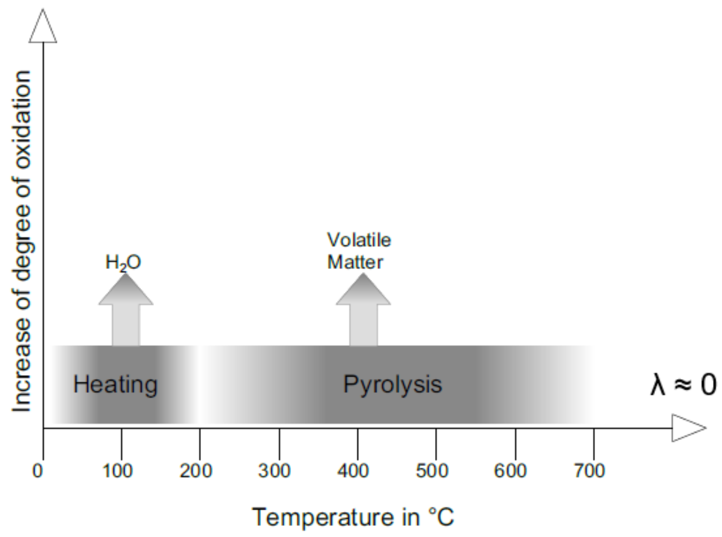

Figure 1 Sequence of pyrolysis with regard to temperature
Source: Own illustration, adapted from KALTSCHMITT [8]

2.2 Gasification

If the target product of the thermochemical conversion is a gaseous fuel (syngas), the pyrolysis process is followed by a gasification process. In this case, oxidant is supplied to the process so that $0 < \lambda < 1$. The reaction is thus called a partial oxidation, meaning that less of the oxidant is used than it is required for complete combustion of the same amount of fuel [9]. Moreover, by the presence of the oxidant, higher temperatures of the reaction are reached, that range between 600 – 1000 °C. As in the case of pyrolysis, gasification is an endothermic process.

The (main) final product of the gasification process of the gasification is syngas that includes components such as methane (CH_4), carbon dioxide (CO_2), carbon monoxide (CO), water (H_2O) and hydrogen (H_2) [9]. The type and proportion of each component thereby depends on the biomass feedstock and the operating conditions of the gasification. In addition to syngas, gasified charcoal is obtained as well. This differs in its properties from pyrolyzed charcoal, as it has a lower content of polycyclic aromatic hydrocarbon and tar. The energy content of the gasified charcoal, i.e., the lower heating value (LHV) depends on the biomass feedstock and operating conditions. The charcoal can potentially be further used for oxidation, i.e., combustion to obtain thermal energy. Syngas as well, can further be used for oxidation, due to its combustible components, e.g., CH_4. For the oxidation to take place, a sufficient supply of an oxidant ($\lambda \geq 1$) is required. The products of the oxidation reaction of syngas depend on the supply of oxidant: in case of insufficient supply of oxidant, CO and other non-oxidized or unoxidized or partially oxidized higher hydrocarbon compounds are formed. Under sufficient supply of oxidant, it comes to a full oxidation of the fuel with products, mainly CO_2 and H_2O [8]. The sequences of gasification and oxidation are shown in Figure 2. In Figure 2, the light grey procedures demonstrate an endothermic process whereas the dark grey procedure indicates an exothermal process.

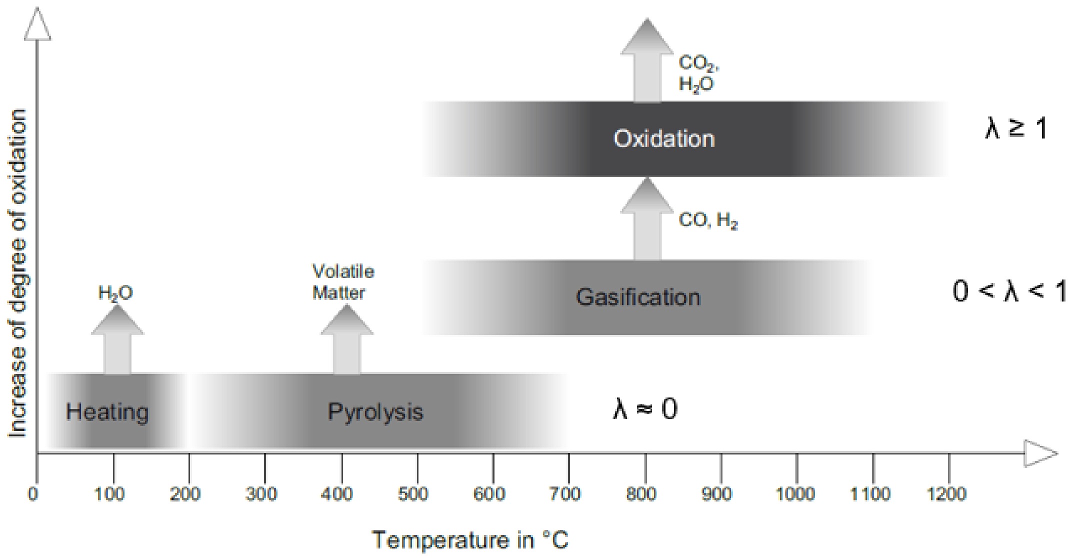

Figure 2 Sequence of gasification and oxidation with regard to temperature
Source: Own illustration, adapted from KALTSCHMITT [8]

2.3 SynCraft gasification technology

There are various gasification technologies on the market, which are classified according to their construction design, working principle and requirements. Common gasification technologies are moving bed/fixed bed gasifiers, which are used when the gasification reactor is fed with relatively large particles of biomass feedstock. If smaller particles of biomass feedstock are used, a fluidized bed gasifier is used [9]. Please refer to DE ET AL. [9], who provide a good overview of the various technologies.

The floating fixed bed gasification technology is a relatively recent gasification technology, developed by the Austrian company SynCraft. Sustainably obtained agroforestry residues are used as biomass input and get finally converted into heat and electricity through the sequential processes of pyrolysis, gasification, and oxidation of syngas. Thereby, the gasification technology concept consists of a stable packed bed of a solid-gaseous mixture that is formed in the gasification reactor. The bed floats on the input gas stream, consisting of pyrolysis gas and oxidant. In comparison to other gasification technologies, the tar content in the obtained syngas is lower and therefore provides a better quality for further oxidation [10]. In addition, the gasified charcoal obtained from SynCraft gasification processes has a relatively high carbon content of ~ 90 % (the currently known lowest value is 80 % [11]). A design sketch of a typical SynCraft gasification system is shown in Figure 3. The individual processes of the gasification system are explained in more detail in chapter 5.2.

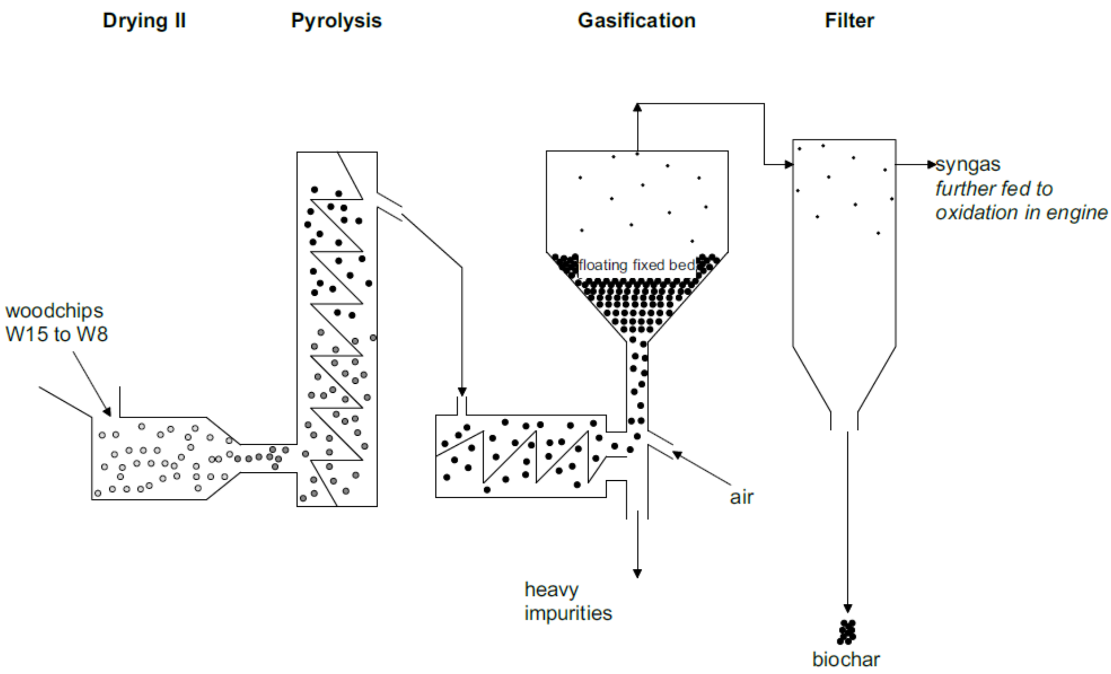

Figure 3 Design sketch of a typical SynCraft gasification system

Source: Own illustration, adapted from HUBER ET AL. [10]

3. Biochar

So far, charcoal has been reported as one of the products obtained from pyrolysis and gasification, respectively. For this study, however, it is important to distinguish between charcoal as a general product from thermochemical conversion processes and biochar in particular. According to the EUROPEAN BIOCHAR INDUSTRY (EBI) [12], biochar

> *"[…] is produced by pyrolysis of sustainably obtained biomass under controlled conditions with clean technology and is used for any purpose that does not involve its rapid mineralisation to CO_2 and may eventually become a soil amendment. […] Gasification is understood as being part of the pyrolysis technology spectrum and can, if optimized for biochar production, be equally certified under the EBC."*

To ensure the quality standards of biochar production and biochar as a product, EBI has developed a certificate (European Biochar Certificate [EBC]) and accompanying criteria that must be met in order to receive the EBC. It´s a voluntary industry standard in Europe which criteria relate to the biomass feedstock, the production method, the properties of the biochar, and the method of application. For further information on EBC, see [12].

Since the object of this work is biochar that meets the EBC criteria, the term "biochar" will further be used throughout the thesis. This is done also in literature research even though the EBC criteria may not always be met. In the next sections, general information on the background of biochar formation, starting with the photosynthesis process of the biomass, and environmental potentials of biochar are described.

3.1 CO_2 sequestration by means of photosynthesis

Plants procedure photosynthesis, that relies on the removal of CO_2 from the atmosphere. The plant embodies, i.e., stores, the carbon fraction of CO_2 while the fraction of O_2 is released back to the atmosphere. The stored carbon in the plant is accounted as biogenic carbon henceforth, where 1 kg of biogenic carbon corresponds to 3.67 kg of biogenic CO_2[1] [13]. However, in case of biomass decay, the biogenic carbon reacts with O_2 and is released back into the atmosphere as biogenic CO_2. The same effect occurs, when using biomass for energy production purpose; the oxidation of biomass leads to the release of biogenic CO_2 emissions into the atmosphere.

CO_2 sequestration describes the overall procedure of CO_2 removal from the atmosphere and long-term storage of biogenic carbon. One way to obtain CO_2 sequestration is the conversion of biomass to biochar and application of biochar to soil, with no further thermochemical conversion following.

The processes of CO_2 removal, release of biogenic CO_2 back to the atmosphere and CO_2 sequestration are shown in Figure 4.

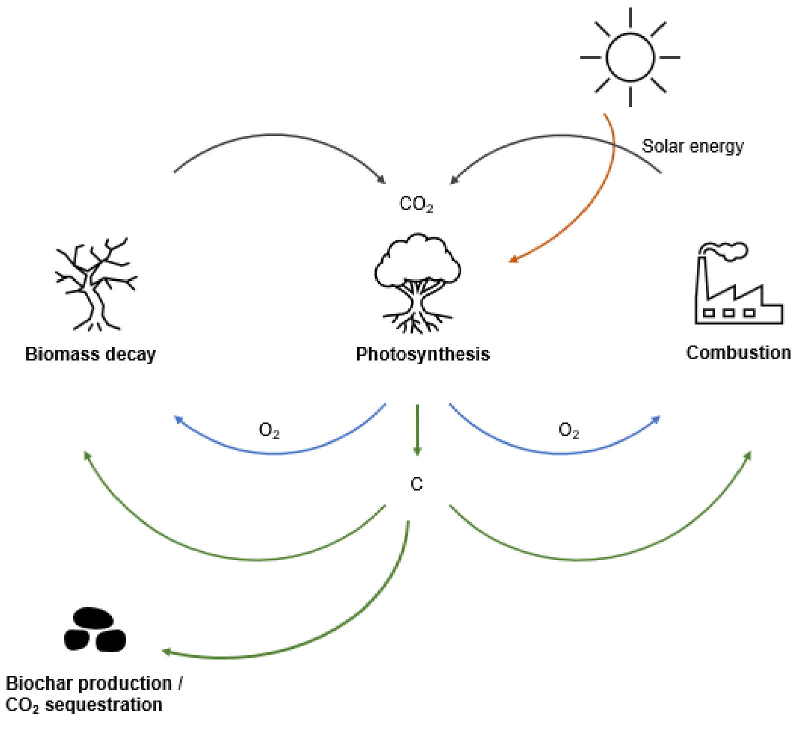

Figure 4 Scheme of photosynthesis, release of biogenic CO_2 and CO_2 sequestration
Source: Own illustration

[1] Results from molar mass: C = 12 kg/kmol, CO2= 44 kg/kmol. Conversion rate is therefore 3.67.

3.2 Biochar stability

High resistance to biodegradation due to its highly condensed aromatic structure is one of the biochar characterization properties, as WANG AND WANG [14] have reviewed. To show an indication of resistance to biodegradation, the carbon stability factor (CSF) is introduced and defined

> *"[…] as the carbon fraction remaining in soil after a defined amount of time, […] often used to evaluate the carbon sequestered." [26].*

The introduction of CSF therefore is based on the properties of biochar, as it consists of each a recalcitrant (stable) and labile fraction. Because the latter decomposes within hours up to a few years, the labile carbon fraction is not considered to contribute to a long-term storage of biogenic carbon. However, the stable carbon fraction is considered to store biogenic carbon for hundreds up to thousands of years. For example, WANG ET AL. [15] consider a mean residence time of biochar, that only refers to the stable carbon fraction, in soil of 500 years, whereas the mean residence time of the labile carbon fraction is set to one year. Frequently, a relationship of stable / labile parts of 80:20 % (CSF of 0.8) is used ([16], [17], [4]).

3.3 Environmental potentials of biochar use

In addition to its potential for CO_2 sequestration, biochar is often discussed in the context of several other environmental benefits that can be particularly useful in agriculture. A broad range of reviewed papers, which focus on biochar in context of environmental management, preparation, modification and application, are provided by MATUSTIK ET AL. [18], ZHANG ET AL. [19], KAVITHA ET AL. [20] as well as WANG AND WANG [14]. Thereby, improvement of soil fertility through biochar application plays a dominant role, enhanced by increase of soil organic carbon (SOC) exchange, i.e., carbon contained in soil, reduction of acidity and leaching of nutrients, increase of ion-exchange and water holding capacity, [21], [14], as well [18]. Based on literature research, however, there´s no consistent reporting of results in terms of SOC exchange, since increase and decrease of CO_2 emissions of soil after biochar application were both observed [14].

3.4 Biochar use in cascade in agriculture

As reported by WEBER ET AL. [22], cascade use of biochar can be useful in agriculture, e.g., in livestock husbandry. Thereby, cascade components can include biochar use as feed additive, stall litter, compost additive and manure treatment. The authors assumed that organic nutrients such as nitrogen (N), phosphorus, and potassium accumulate in the biochar at each stage of use. For example, biochar binds N, thereby reducing its leaching and therefore consequently prevents release N_2O and ammonia (NH_3) emissions. Finally, in its end stage as soil application, biochar can therefore be an efficient organic fertilizer and increase SOC exchange.

4. Literature research

The current interest in biochar´s role for CO_2 sequestration and potential benefits in agricultural context is reflected by a multitude of publications. To obtain an indication on biochar's environmental impacts, multiple of studies conducted LCA on biochar systems, e.g., production and or application of biochar.

Literature research was done to identify key findings of LCA on biochar that is obtained from gasification and pyrolysis as well as on biochar use in agricultural context. Regardless of either gasification or pyrolysis was used as thermochemical conversion process for biochar production, the results ultimately show an overall trend of effectiveness of biochar application to agricultural soil. However, effects in other applications than to soil are different and do not allow for direct comparison [18] due to the variability of biochar production and use.

4.1 Publications of LCA on biochar from gasification

In principle, only few publications were found for LCA conducted on biochar obtained from gasification processes. This may be due to the fact that in a gasification process the focus is not on the production of biochar but on the syngas.

As already mentioned, KÄPPLER [7], conducted LCA on the same wood gasification plant as in the current work. The functional unit was set to 1 kWh of energy, i.e., combination of heat and electricity, and reference flow was set to 1 kg of woodchips (water content 15 %). Unlike other studies, the study takes the construction and demolition of several buildings and the heating grid into account. The assessment results in a GWP of - 0.0368 kg CO_{2eq} per 1 kWh with consideration of CO_2 sequestration potential of biochar, this corresponds to - 0.01 kg CO_{2eq} per 1 MJ.

PUETTMANN ET AL. [23] conducted LCA on biochar production from forest residues, using various portable systems and comparing it to the current practice of pile burning of forest residues in British Columbia, Canada. One of the portable systems used (BSI, i.e., Biochar System Incorporated) is a down-draft gasifier, that converts the biomass feedstock into biochar throughout different stages. When used at remote biochar production locations, i.e., in woods, a diesel generator or biomass gasifier (power pallet) is used for power supply, that is 20 kW. When the BSI system is used in town, grid electricity is used. The biomass feedstock used is treetops lying on the ground and medium chipped pulpwood. The cradle-to-gate assessment was performed using three different functional units: 1 ton of biochar, percentage of carbon sequestered in the biochar, and 1 ton of forest residue. Results on GWP are obtained that range between -1,700 kg CO_{2eq} up to -2,600 kg CO_{2eq} each per 1 ton of biochar, depending on the source of power and type of feedstock. Best results on GWP are obtained when using electricity from the electricity grid for power supply, even though there´re extra emissions occurring for the transportation from remote locations into town. At remote locations, the results on GWP perform better, when using the power pallet for power supply instead of diesel generator. Further, the amount of carbon stored in medium chipped pulpwood was identified to be higher compared to tops left on ground.

Basically, there are different approaches on how biogenic CO_2 emissions occurring from thermochemical conversion of biomass can be considered in LCA. The review from UBANDO ET AL. [24] is used as an illustration, although it does not focus specifically on biochar but includes other bioenergy products such as bio-oil and syngas as well. In the review, various LCA studies on biochar, bio-oil, and syngas from microalgal and lignocellulosic biomass and various thermochemical conversion processes were analyzed. The results on GWP for gasification studies are shown in Figure 5. Thereby, the presented functional unit of 1 MJ of energy is a conversion of the original functional units to draw comparisons between results. For GWP, negative results were obtained by MORENO AND DUFOUR [25], RENÓ ET AL. [26], CARPENTIERI ET AL. [13], GONZALEZ-GARCIA ET AL. [27] and LUTERBACHER ET AL.[2]. The spread between their results is 0.6 kg CO_{2eq} and founded by different biomass feedstock, target products and therefore technology conducted as well as calculation set up:

RENO ET AL. [26] conducted LCA on the production of methanol from sugarcane bagasse in Brazil, thereby setting functional unit to 1 kg of methanol produced. The sugarcane used for gasification is considered to absorb (-) 4.22 kg CO_2 per 1 kg of methanol produced from the atmosphere during its growth phase. The biogenic CO_2 emissions occurring from the gasification of the sugarcane bagasse were not taken into account. For GWP, the assessment results in - 2.284 kg CO_{2eq} per 1 kg of methanol produced. MORENO AND DUFOUR [25] conducted LCA on hydrogen production from biomass gasification, with a functional unit of 1 Nm^3 of hydrogen. Assessing four different biomass feedstocks (pine, eucalyptus, almond pruning, vine pruning), a net negative result for GWP was obtained only for eucalyptus, that is ~ -0.1 kg CO_2 per 1 Nm^3 hydrogen, since it´s assumed to have a higher amount of biogenic carbon contained compared to the other feedstock assessed. CARPENTIERI ET AL. [13], conducted LCA on biomass gasification with integrated CO_2 removal. Using poplar as biomass feedstock, the functional unit was set to 1 MJ of energy. The authors obtained negative results for GWP, that is - 0.165 kg CO_2 per 1 MJ energy, due to accounting the plant growth of biomass as negative due to the CO_2 fixation by means of photosynthesis. The later occurring biogenic CO_2 emissions due to gasification were not taken into account. Moreover, parts of the CO_2 emissions occurring due to the produced syngas is additionally removed by chemical absorption during operation (CO_2 removal efficiency is about 80 %) to reduce GHG emissions.

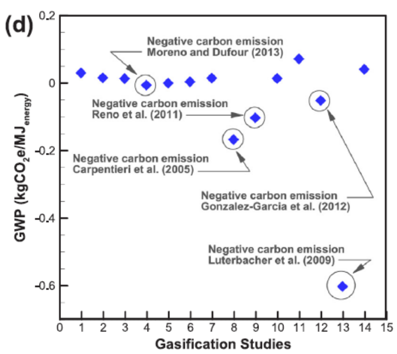

Figure 5 GWP of different energy carriers generated though gasification.
Source: UBANDO ET AL. [24]

[2] Paper not accessible.

Based on the review of UBANDO ET AL. [24], different approaches on how biogenic CO_2 emissions due to thermochemical conversion can be accounted in LCA are demonstrated: first, there´s the approach of accounting biogenic CO_2 emissions as neutral, i.e., the CO_2 sequestration due to photosynthesis during plant growth and the biogenic CO_2 emissions occurring due to thermochemical conversion is considered as offsetting each other. This approach is based on the assumption that emissions from biomass have no impact on GWP according to IPCC standards [28]. However, this can be critical in LCA because of the risk of a lack of transparency about where sequestration and emissions occur in the assessed system. In addition, CO_2 neutrality of biomass is not automatically valid for all biobased products, as SINGH [29] illustrates. As a counterpart to this approach, SINGH [29] recommends to account biogenic carbon clearly as a negative emission, i.e. CO_2 reduction to ensure transparency and consistency in the LCA by tracking all relevant flows in all life cycle stages of the assessed product or system.

Further research for LCA on gasification on woody biomass was done by RAMACHANDRAN ET AL. [16] who considered co-gasification of woody biomass and sewage sludge. Thereby, an existing system of separate sewage sludge incineration and incineration of woody biomass were compared to common co-gasification of both feedstocks. The FU was set of 1 kg of mixture of sewage sludge and woody biomass. Due to the processes of biochar production, biochar distribution and used for soil application, the result for GWP is - 0.4384 kg CO_{2eq} per 1 kg of mixture of sewage sludge and woody biomass. Thereby, an amount of - 0.229 kg CO_{2eq} per 1 kg of mixture of sewage sludge and woody biomass was considered and identified as being crucial for the total result. For the woody biomass, a CSF of 0.8 was considered, and carbon content of biochar was assumed to be 80 %.

Another study focusing on gasification of woody biomass was found by PA ET AL. [30], who conducted LCA for a wood gasification plant for district heating in British Columbia, Canada. The gasification plant is intended to replace the current combustion of natural gas and to provide heat only. Various scenarios, including current operations, were evaluated with the inclusion of various feedstocks such as wood pellets and wood waste. The functional unit of the assessment is set to 1 ton of wood pellets, and allocations were made on a mass basis. Harvesting and transportation processes were included, and CO_2 emissions were accounted for as either fossil or biogenic, depending on the scenario. In the scenario of gasification of wood pellets with emission control, the result for GWP is $1.0*10^{-7}$ kg CO_{2eq} per 1 ton of wood pellets. For wood waste with emission control, the result for GWP is $1.1*10^{-7}$ kg CO_{2eq} per 1 ton of wood waste. In both scenarios, the harvesting of wood and the transportation of biomass by heavy duty trucks were identified as the main contributing processes. However, the production of biochar was not in the authors focus which explains that there´s no crediting of negative emissions accounted.

4.2 Publications of LCA on biochar from pyrolysis

The production of biochar from pyrolysis appears to be the more common technology at present, compared to biochar production from gasification, reflected in a larger number of studies. Since biochar from pyrolysis doesn´t allow for direct comparison, only few studies are presented in the following that focus on biochar use cases in agriculture.

General overviews on pyrolyzed biochar potentials in terms of GHG reductions, including CO_2 sequestration, as well as on biochar uses going beyond soil application with focus on tar removal, use as a fuel, for containment management, as an adsorbent or for electrochemical applications is provided by YOU ET AL. [31] as well as ZHANG ET AL. [19].

Amongst other things, AZZI ET AL. [4] analyzed the effects of cascade use of biochar in livestock husbandry in Sweden. Thereby, pyrolyzed biochar was used as animal feed additive, for manure treatment and eventually for soil application. As functional unit, 1 ton of dry woodchips (water content 10 %) was used. As feed additive, 0.12 kg of biochar was fed per cow and per day to dairy cattle. Using biochar for manure treatment, a mixing rate of 3 % of biochar to manure is considered, while the application rate of the mixture of biochar and manure to soil is set to 43 tons per ha, thereby including 25 tons per ha of fresh manure and biochar of 0.8 tons per ha. The pyrolyzed biochar was considered having a carbon content of 80 % and a CSF of 0.8. Three different scenarios (worst, average, best) were created for the assessment, assuming different potentials in terms of emission reductions factors of gases occurring due to enteric fermentation of manure, emissions occurring due to indoor storage of manure, applications of manure and mineral fertilizer as well as soil as a CH_4 sink. For the worst scenario, the assessment results in a GWP of - 1.7 kg CO_{2eq} per 1 kg of dry woodchips, with CO_2 sequestration potential of biochar contributing to 90 %. For the average scenario a GWP of - 3.3 kg CO_{2eq} per 1 kg of dry woodchips is obtained with CO_2 sequestration potential of biochar contributing to 30 %. The best-case scenario results in a GWP of - 4.9 kg CO_{2eq} per 1 kg of dry woodchips and contribution of CO_2 sequestration potential of biochar by 50 %.

HAMEDANI ET AL. [17] performed LCA on biochar production and soil application in Belgium. Two scenarios were created, that use two different biomass feedstocks for the production of biochar: willow woodchips and pig manure. The functional unit was set to 1 ton of biochar produced. For both scenarios, negative results for GWP were obtained, yielding in - 2.1 kg CO_{2eq} per 1 kg of biochar produced for willow woodchips and - 0.5 kg CO_{2eq} per 1 kg of biochar produced of pig manure. The different results for both feedstocks are due to the different carbon contents of biochar: 75 % for willow whereas it´s only ~ 34 % for manure (in both cases of the dry and ash-free original feedstock biomass weight). In both scenarios, the CO_2 sequestration potential of biochar is attributed to soil application and contributes the most to the total results. Other contributions to CO_2 emission reduction were identified as heat and electricity substitution and reduced fertilizer production.

Moreover, YANG ET AL. [32] conducted LCA of biochar application in agriculture in China. For biochar production, crop residues from grain, bean, tuber, oil crop, cotton, sugarcane, and hemps were used as biomass feedstocks. An input related functional unit was used and set to 1 ton of crop residues. The assessment led to results for GWP of - 0.9 kg CO_{2eq} per 1 kg of crops residues for biochar production by slow pyrolysis. A sensitivity analysis was performed with the following parameters found to be critical: biochar yield, carbon content in biochar, electricity conversion efficiencies of bio-oil and pyrolysis gas.

4.3 Conclusions on literature research and research questions

A conclusion on literature research is drawn by the following points: First, the number of publications on LCA of biochar from pyrolysis exceeds that from gasification. The little number of studies focusing on LCA of biochar from gasification is therefore considered as a research gap and more work is encouraged to be done in this field. Second, the LCA results of biochar vary widely due to variables in the system, e.g., the biomass feedstock used, and the thermochemical conversion chosen. In terms of the functional unit, both input and output related functional units were found. Further variables identified are the system boundaries set, e.g., the assessment from cradle to grave. Moreover, the motivation of the research, i.e., where the focus on the individual study is put does have influence on the results and transparency of the study. Third, different approaches on how the CO_2 sequestration potential of biomass and the biogenic CO_2 emissions occurring during thermochemical conversion of biomass are accounted in LCA were reflected, e.g., assuming CO_2 neutrality clearly pointing out the emissions where they occur within the system.

With respect to the conclusions drawn on literature research, the current work is focusing on contributing to the field of research that focus on LCA on biochar obtained from gasification by working on the following research questions:

1. What are the environmental impacts of biochar, heat, and electricity from a wood gasification plant?
2. What are the environmental impacts of the further cascade use of biochar on farm?

Other than the work of KÄPPLER [7], it´s clearly distinguished between the different energy forms, i.e., heat and electricity. Further, the use of biochar for manure treatment and soil application is integrated.

5. System description

To assess the environmental potentials of biochar in practice, LCA was conducted on a wood gasification plant and a farm, both located in Vorarlberg, Austria. The wood gasification plant Energiewerk Ilg (Energiewerk) is set up as a Combined Heat and Power (CHP) plant, producing electricity, heat, and biochar. The gasification technology used is the earlier introduced floating fixed bed gasification technology. In 2020, the production volume of biochar, heat on high temperature level and electricity were 244,972 kg, 3,008 MWh and 1,765 MWh, respectively. The biomass required for gasification is produced from local woods nearby the gasification plant. The farm Martinshof purchases biochar from Energiewerk and uses it for manure treatment and soil application.

For the assessment, relevant processes are identified and differentiated according to their level of aggregation. There are four core processes that represent the highest level of aggregation, including biomass production, gasification, energy production, and biochar use. Each of the core processes includes several main processes. At the lowest level of aggregation, there are sub-processes contributing to the main processes. An overview on the core and main processes is given in Figure 6. All the associated processes are illustrated below and described in chapters 5.1 - 5.5.

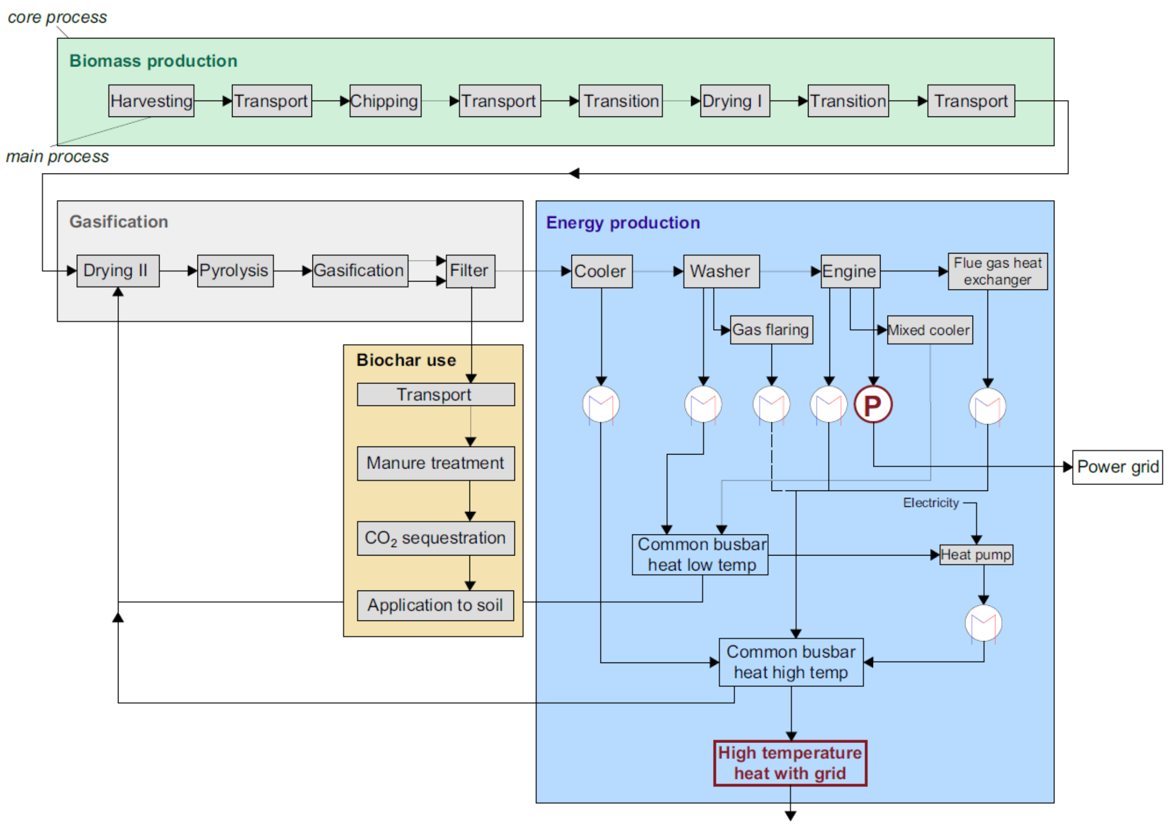

Figure 6 Core and main processes assessed on LCA of the gasification plant and farm
Source: Own illustration

5.1 Biomass production

The core process biomass production includes the harvesting of wood, i.e., felling and delimbing of logs, and further processing of the logs to woodchips. Different transportation and transitions of the logs and woodchips are needed in between the processing stages.

The core process biomass production includes eight main processes as shown in Figure 7 which are further described below.

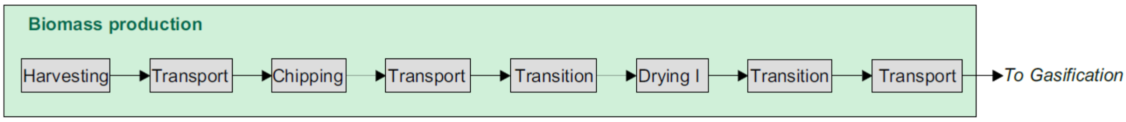

Figure 7 Core process biomass production and contributing main processes
Source: Own illustration

The biomass feedstock is mainly spruce wood which is harvested within 10 km radius from the gasification plant. As to be seen in Figure 8, spruce wood is mostly located in steep areas which is why different harvesting methods are required. Not all areas highlighted in Figure 8 are used for harvesting, but it does give an indication of the topography and relevant locations for the further assessment.

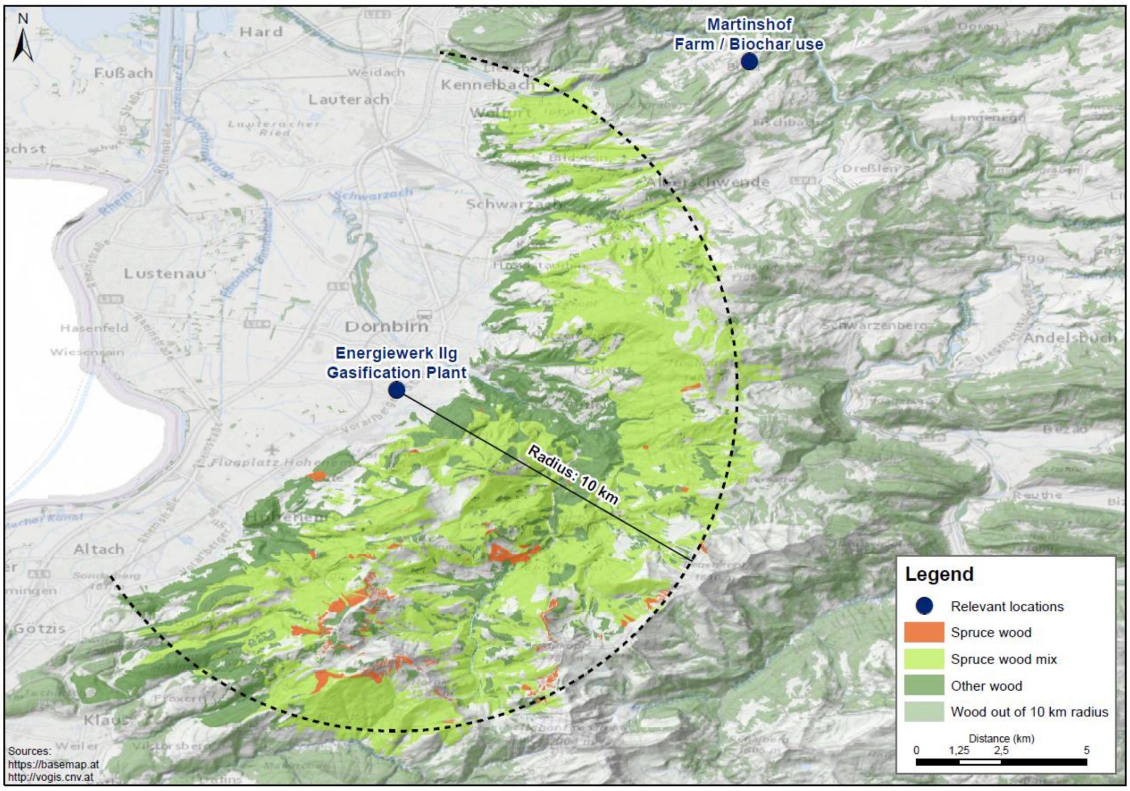

Figure 8 Overview on locations of spruce wood which is used for biomass production and locations of the gasification plant and farm
Source: Own illustration based on GIS sources (see notes on the map)

Three different *Harvesting* methods are used: 1) motor-manual where wood is primarily harvested by the use of power saws, 2) use of woodliner, crane and power saws in steep situations and 3) liftliner, bagger and power saws that are also used in steep areas.

By tractor and lorry, logs are *Transported* from the harvesting site to a central place nearby, where *Chipping* of logs into woodchips is proceeded by a woodchipper. The processing into woodchips provides a better handling, storage, and drying than leaving the logs in their initial state. Another *Transport* by tractor is needed to transport the woodchips to the storage bunker where the water content is reduced by *Drying I*. According to MÄSER [33], the woodchips have an initial water content of 40 % (woodchips W40). By using heat from a biogas plant for the drying process, a water content of 15 % is achieved (woodchips W15) and the LHV of woodchips is increased, making the woodchips W15 more efficient for the following thermal conversion processes. The *Transition* of woodchips W15 at the storage bunker, i.e., load on and off is done by a wheel loader. After transition follows another *Transport* of woodchips W15 from the storage bunker to the gasification plant (~ 3 km distance) by tractor.

5.2 Gasification

As illustrated in Figure 9, the core process gasification consists of four main processes which are *Drying II*, *Pyrolysis*, *Gasification* and *Filter*. The woodchips W15 are fed into *Drying II* bunker where the water content is reduced from 15 % to 8 % (woodchips W8) to further increase the LHV of the woodchips. The required heat is taken from different exothermal processes, i.e., processes within the gasification plant that take place later in the process. Subsequently, the woodchips W8 are fed into the *Pyrolysis* reactor where they are pyrolyzed and a mixture of pyrolysis gas and pyrolyzed biochar is obtained. The pyrolysis reaction takes place at a temperature of ~ 410 °C. In a next step, the pyrolysis gas and pyrolyzed biochar are both fed into the *Gasifier* via a screw conveyor. For the gasification reaction to take place, air is used as an oxidant and temperatures reach up to ~ 780 °C. The outputs of the gasifier are syngas and biochar. Heavy contaminants such as stones and other inorganic material are removed at the outlet of the gasifier due to force of gravity. Solid and gaseous components, i.e., biochar and syngas are separated via the *Filter* and the syngas is further processed in the core process energy production. Biochar is filtered out of the gasification system and filled into big bags. Due to the high temperatures of biochar, water is added to cool the biochar and to prevent the risk of fire. The biochar filled in big bags therefore has a water content of 35 %.

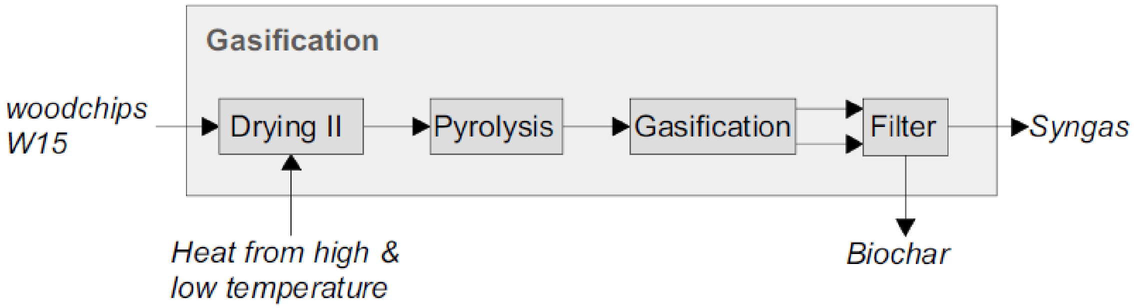

Figure 9 Core process gasification and contributing main processes
Source: Own illustration

Based on the provided data from the operator of the gasification plant, the following yield of biochar was obtained in 2020:

Input	Amount	LHV
Woodchips (Dry Matter [DM])	1.353,462 kg	7.067,816 kWh
Biochar (DM)	244,972 kg	2.041,433 kWh

Table 1 Total amount and LHV of woodchips and biochar in 2020

Source: Energiewerk Ilg

Further properties of the biochar obtained are listed in Table 2.

Component	Value
Carbon content (DM)	90 %
Ash (DM)	10 %
Carbon stability factor (assumption)	0.8
Water content	25-30 %
LHV (DM)	30,000 kJ/kg [11]
Bulk density	230-250 kg/m^3
pH	10.5

Table 2 Properties of biochar obtained from core process gasification

Source: ENERGIEWERK [34] and MANAGEMENT CENTER INNSBRUCK (MCI) [11]

5.3 Energy production

In the core process energy production, the syngas obtained from gasification is further processed throughout different stages to be eventually used to produce electricity and heat by combustion in the engine. The main processes contributing to the core process of energy production are shown in Figure 10. A more detailed illustration of the main processes is provided in Figure 11.

The syngas is led from *Filter* to *Cooler*, where heat on high level temperature is obtained from. Next, the syngas enters the *Washer*, where a cooling process takes place: water is sprayed into the syngas to enable cleaning, cooling and condensing. The condensate is drafted out at the outlet of the washer. The heat obtained from the washer is directed to the common busbar for heat on low temperature level. A combustion of small amounts of the syngas is processed in the *Gas flaring*, whenever the syngas doesn´t have the quality sufficient for the engine, e.g., in case of a startup, or when there´s too much syngas compared to the engine's capacity. For gas flaring, propane is used as an additive to support the combustion process. The syngas is eventually led to the *Engine* where combustion of the syngas takes place to further obtain electricity and heat. Directly occurring heat due to the exothermal reaction of the combustion is on high temperature level and fed into the common busbar for heat on high temperature level. Heat on low temperature level obtained from the engine is fed into the *Mixed cooler* and eventually into the common busbar for low temperature heat. Flue gases occurring due to the combustion of syngas in the engine are fed into the *Flue gas heat exchanger* where heat on high level temperature is obtained from.

About 50 % of the heat from the common busbar of heat on low temperature level is used for Drying II process that´s included in the core process gasification. The remaining amount of heat from the common busbar of heat on low temperature is led into the *Heat pump* which provides heat on high temperature level under additional supply of electricity.

Most of the total amount of heat in the common busbar of heat on high temperature is directly used for district heating and fed into the heating grid and is transported to customers. Further, about 7 % of heat on high temperature level is led from the common busbar of heat on high temperature to Drying II.

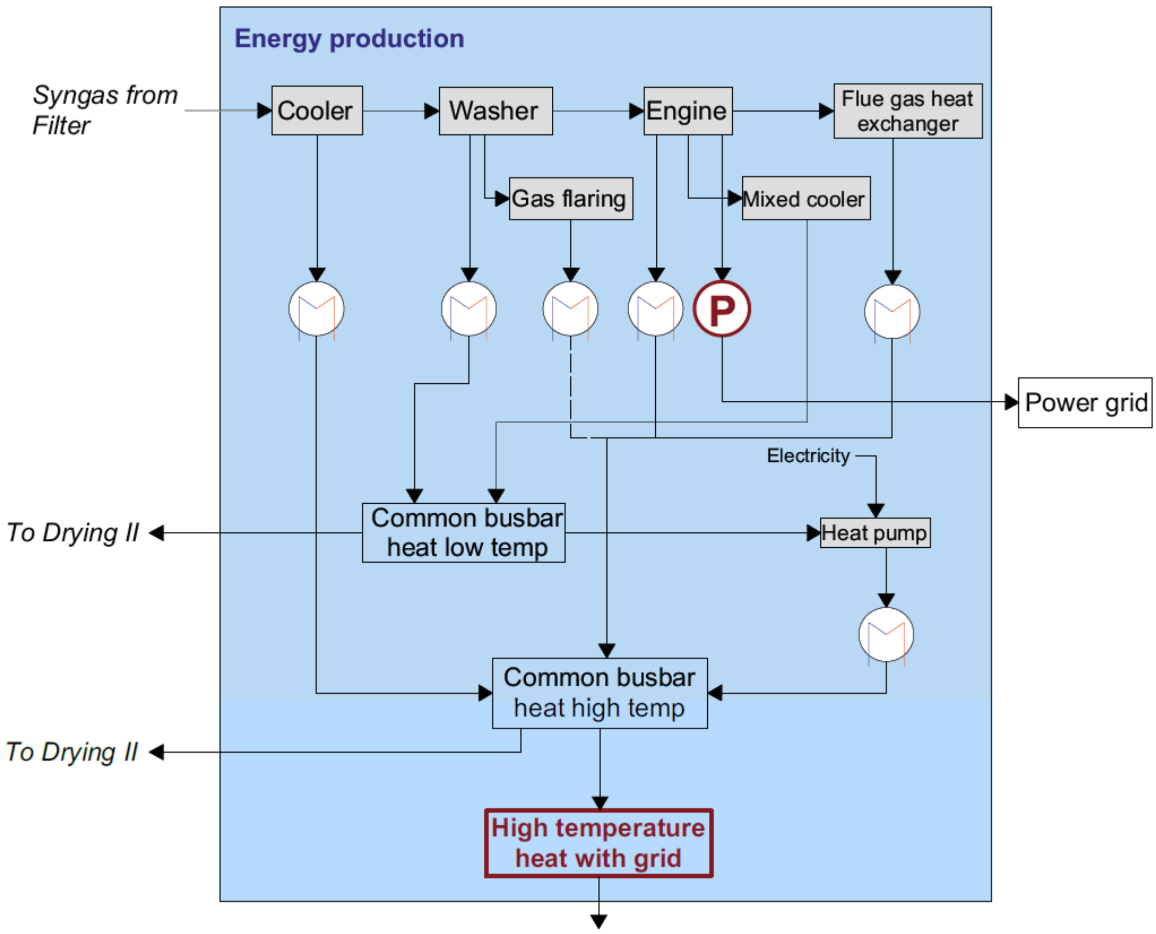

Figure 10 Core process energy production and contributing main processes
Source: Own illustration

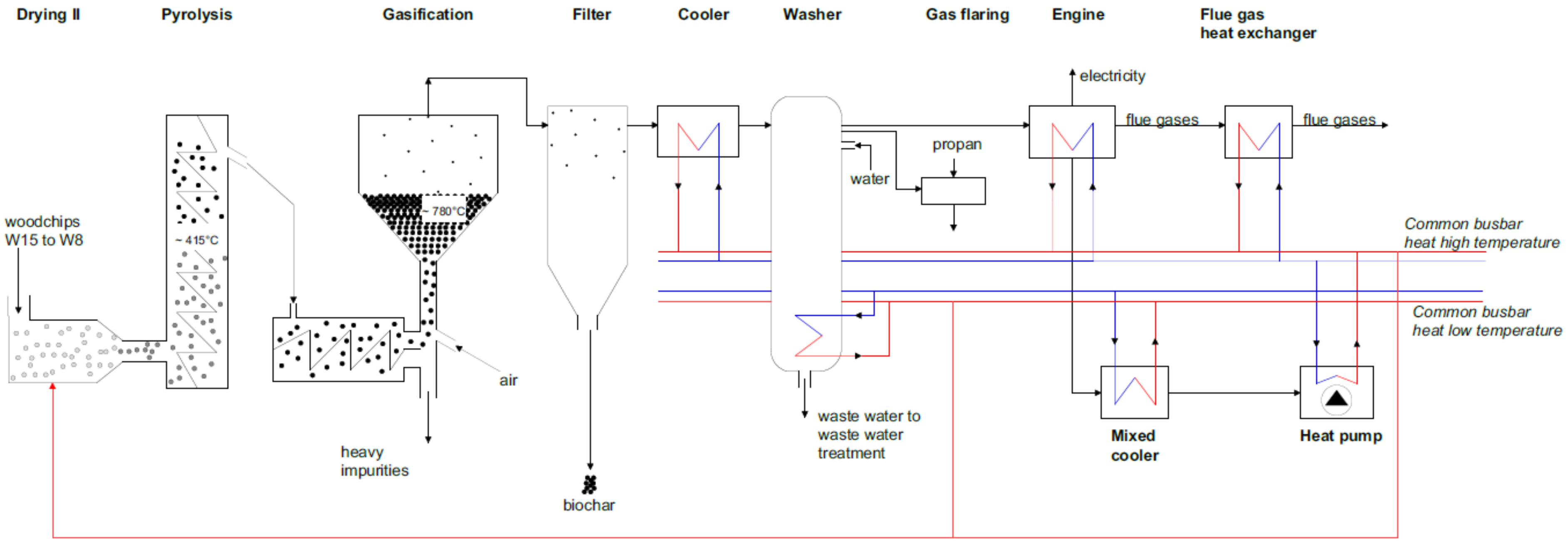

Figure 11 Scheme of the core processes gasification and energy production with contributing main processes
Source: Own illustration adapted from ENERGIEWERK [34] and SYNCRAFT [35]

Emissions occurring due to the combustion of syngas in the engine are relevant since they contribute to the environmental impacts of the gasification plant. The amount of emissions was derived from an emissions test conducted in April 2021 and are provided in the unit of mg per m^3 flue gas which makes the volumetric flow rate of the flue gas necessary to be known. The calculation is provided in full in the appendix, results are presented in Table 3. A sketch of the combustion is shown in Figure 12.

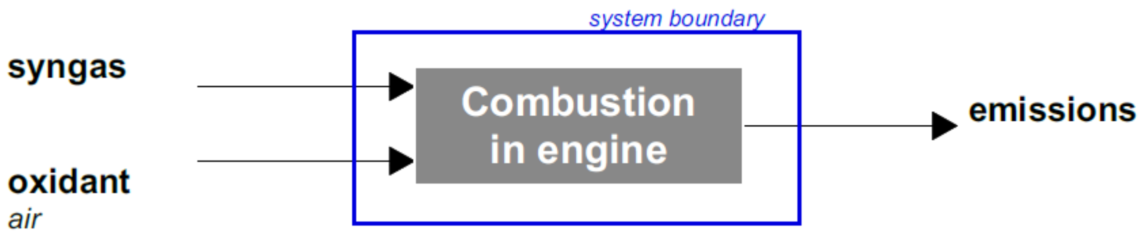

Figure 12 Sketch of combustion of syngas in engine with emissions occurring
Source: Own illustration

Component	Measured	Per reference flow (1 kg W40)
O_2	7 %	0.4676 kg
CO	179 mg/m^3	$8.67*10^{-4}$ kg
NO	216 mg/m^3	$1.05*10^{-3}$ kg
NO_2	2 mg/m^3	$9.69*10^{-6}$ kg
NO_x	333 mg/m^3	$1.61*10^{-3}$ kg
CO_2	7.8 %	0.716 kg

Table 3 Emissions obtained from emissions test and per reference flow
Source: Own calculation with data from ENERGIEWERK [34]

5.4 Constructions

The impact of buildings and construction systems required for the operation of the gasification plant are considered in LCA. Table 4 gives an overview on their functions.

Construction	Function
Heating grid	Infrastructure needed to deliver heat on high temperature level to customers and return cooled down backflow from and to gasification plant.
Main building	Encloses gasification system and day bunker.
Storage bunker	Temporarily storage of woodchips and Drying I process to reduce water content from 40 % to 15 %.
Gasification system	Encloses building and energy requirements.

CHP	Encloses the SynCraft-technology including pyrolysis, gasification, filter, washer, cooler, gas flaring, CHP, flue gas heat exchanger.
Heat pump	Conversion of heat on low temperature level to high temperature level.

Table 4 Construction of the gasification that are considered in LCA

Source: Own listing

5.5 Biochar use

The main processes within the core process biochar use are demonstrated in Figure 13. At a distance of 20 km from the gasification plant is the Martinshof farm located to where the *Transport* of biochar is carried out. Due to the poultry and cattle, liquid and solid manure is generated that is treated with biochar derived from the gasification plant, i.e., *Manure treatment*. For the liquid manure, biochar is added to reduce odor occurring from the manure which has been shown to be a beneficial qualitative aspect, but it is not further evaluated in the LCA since the transfer of qualitative aspects into quantities are out of scope in this work. Solid manure derived from the cattle stall is stored so that it forms compost and biochar is added to enhance the compost formation. The eventually derived compost from the mixture of solid manure with biochar as well as the mixture of liquid manure with biochar are *Applied to soil*. Both mixtures function as fertilizer, whereas the compost functions as an additional humus on the field as well. The application of both mixtures to soil is processed by both solid manure spreader and liquid manure spreader that can be used for the mixtures with biochar as well.

The manure generated by the cattle and poultry contains N, which further builds up N_2O by various reactions with the atmosphere. The actual amount of N occurring is related to the number of cattle and poultry kept on the farm that generates manure in which N is contained. According to MARTIN [36], about 400 m^3 of total manure and 4,000 kg of N occurred for both cattle and poultry in the year 2020. Regarding the amount of manure generated by cattle, only the amount of manure occurring from within eight months is considered since the cattle are moved to the pastures from September to June. The amount of manure occurring at the pastures is therefore not considered. On the farm, the liquid manure is stored in a bunker with a capacity of 400 m^3 whereas the solid manure is stored just outside the stall in a half-open bunker. The application and mixture of biochar into manure is done mainly manually with a shovel. As for the solid manure in the cattle stall, one third of biochar was added and two thirds of biochar was used for the liquid manure treatment in 2020. This results in a mixing rate of biochar to manure of 2 %.

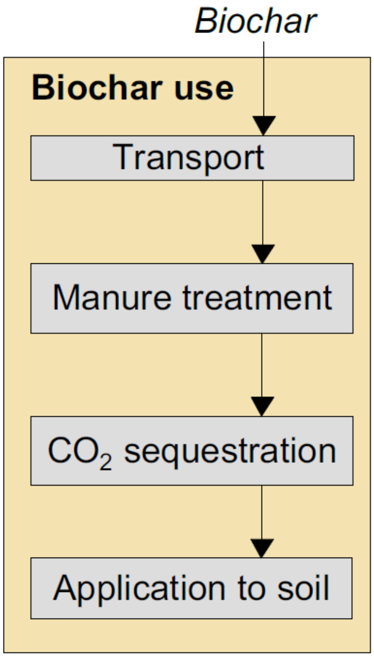

Figure 13 Core process biochar use and contributing main processes
Source: Own illustration

6. Methods

In the following, the conducted LCA method, the method of data collection and the Life Cycle Inventory are described.

6.1 Life Cycle Assessment

The LCA method is a structured, comprehensive and internationally standardised method, that´s used to assess environmental impacts of any good or service, i.e., product. To do so, LCA quantifies all relevant emissions, consumed resources, related impacts on the environment and health and depletion of resources that are associated with the product [37]. For the LCA conducted, the following characteristics are met:

6.1.1 Standardization guidelines

The conducted LCA follows the standardisation guidelines of ISO 14040 which describe LCA framework and principles [38]. According to the ISO 14040 guidelines, the framework includes four phases as shown in Figure 14:

- Goal and scope,
- Inventory Analysis,
- Impact Assessment, and
- Interpretation.

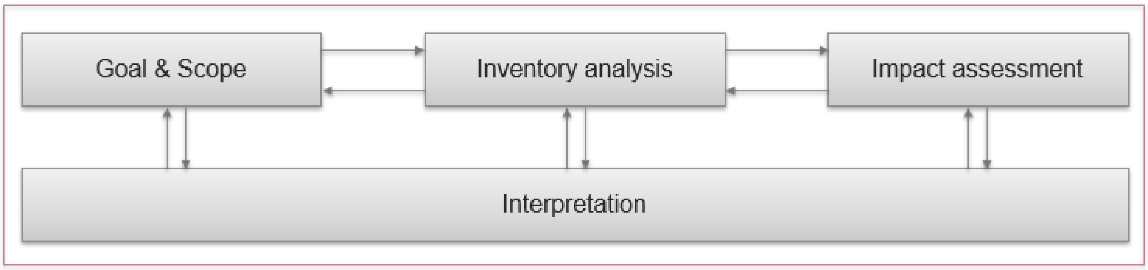

Figure 14 Life Cycle Assessment framework according to ISO 14040
Source: Own illustration, adapted from ISO 14040 [38]

The phase *Goal and Scope* requires the definition of the aim of the study, i.e., the goal and the definition of the assessed system and its processes, i.e., scope. The phase of Life Cycle *Inventory Analysis* (LCI) involves the compilation and quantification of inputs and outputs for the product throughout its life cycle. For instance, resources from nature and emissions to the atmosphere. By the phase of Life Cycle *Impact Assessment* (LCIA), it´s aimed to understand and evaluate the magnitude and significance of potential environmental impacts throughout the products` life cycle. Therefore, emissions and resource extractions during a life cycle are translated into a limited number of environmental impact categories [39]. In the last LCA phase, *Interpretation*, the findings of LCI, LCIA or both are combined with the previously defined goal and scope to draw conclusions and recommendations.

6.1.2 Goal and Scope

The intention of the current work as well as the system boundaries were already introduced in chapter 4.3. Further information on the scope of the LCA is provided by the following points.

6.1.2.1 Functional unit and reference flow

The functional unit demonstrates the basic parameter towards all results are presented. In the present study, LCA is set up as a unit process where results are calculated towards three different functional units: 0.17 kg biochar applied to soil, 4.47 MJ heat on high temperature and 2.82 MJ electricity. The functional units are based on the input related reference flow of 1 kg woodchips W40.

6.1.2.2 Assessment tools

The model was created with the software SimaPro version 9.1, which is supported by the EcoInvent 3 database. The processes were either formed with generic (already existing) processes from the EcoInvent 3 database and adapted with data from the gasification plant and farm. Or new processes were built, also using data from the gasification plant and farm.

6.1.2.3 Allocation

In the LCA conducted, economic allocation is used to allocate environmental aspects of a process towards different co-products. The economic allocation is therefore based on the products market prices. This type of allocation is chosen to emphasis the focus on the produced biochar which has a dominant economic importance for the gasification plant. Other allocation methods are based on mass or physics.

6.1.3 Life Cycle Inventory

The transparency of the LCI and thus of the data is necessary to make the calculations robust, to allow other researchers to replicate the model and to draw comparisons.

As for the method of data collection, primary data was collected on-site by interviews and reports from each the gasification plant operator and farmer. In case no primary data was available, secondary data from generic sources, i.e. the EcoInvent database or data from the LCA study from KÄPPLER [7] was used. Further, in case neither primary nor secondary data was available, assumptions have been made. In the later presented LCI, the information of data source on the processes will be provided.

6.1.4 Life Cycle Impact Assessment

To evaluate environmental impacts of a product, the LCI results are assigned to different impact categories, i.e., different classes that represent environmental issues of concern such as climate change or acidification. The link between LCI results and assignment to an impact category is demonstrated by an example [40]:

CO_2 and CH_4 are both GHG that contribute to the impact category climate change. Global Warming Potential (GWP) is a characterisation factor and a measure for climate change in terms of radiative forcing, that is a category indicator, of a mass-unit of GHG. Assuming that 5 kg of CO_2 and 3 kg of CH_4 are obtained as LCI results, the category indicator result is obtained as followed:

CO_2 is equivalent to GWP = 1

CH_4 is equivalent to GWP = 21

With 5 kg CO_2 and 3 kg CH_4 the calculation is:

$1 * 5 \text{ kg } CO_{2eq} + 21 * 3 \text{ kg } CO_{2eq} = 68 \text{ kg } CO_{2eq}$

Therefore, 68 kg CO_{2eq} is the category indicator result.

The selection of impact categories depends on the method chosen that´s used for LCIA. In the LCA conducted, the ReCiPe method is chosen that determines environmental impact categories at two levels, including 18 midpoint impact categories and 3 endpoint impact categories, see Figure 15. Thereby, a midpoint impact category is problem oriented whereas an endpoint impact category is damage oriented: as for instance, climate change is considered as a midpoint impact category that affects the damage to human health which is considered as an endpoint impact category. For all 18 midpoint categories damage pathways are defined, i.e., the conversion from midpoint impact categories into endpoint impact categories. Although the conversion from midpoint to endpoint category simplifies the interpretation of LCA results, the conversion also increases the results uncertainty [39]. The ReCiPe method requires a type of perspective, that groups different assumptions, e.g., on how policy will handle the environmental impacts within a certain time frame. The perspective chosen in the current LCA is the hierarchist perspective, that is set to a 100 years' timeframe [41].

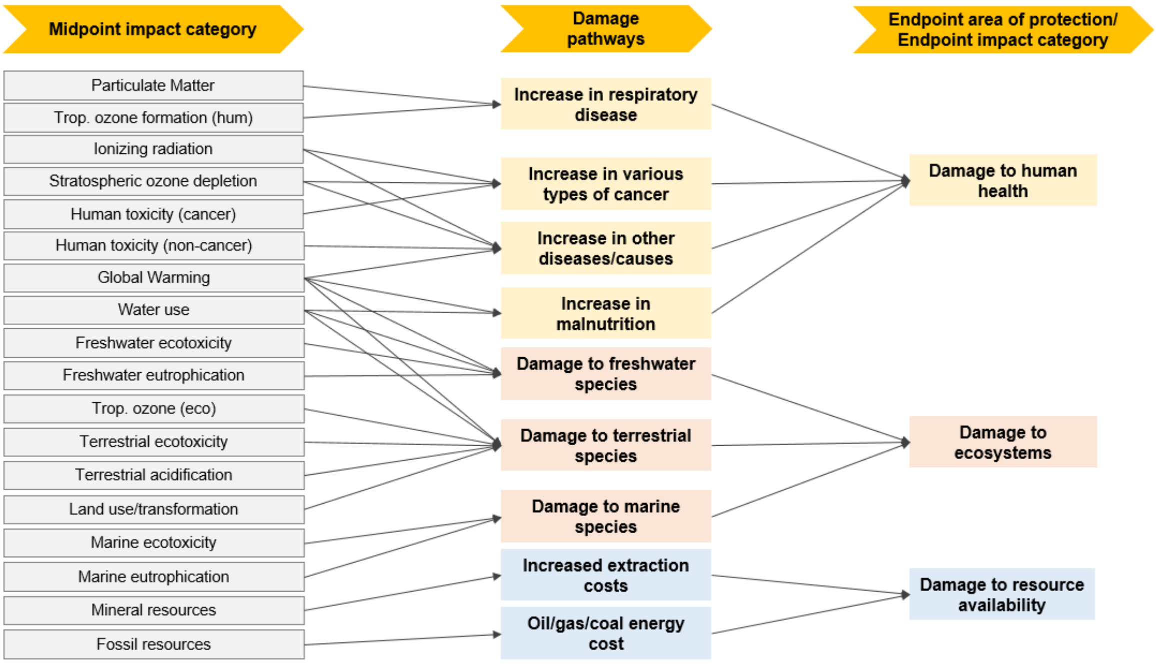

Figure 15 Overview on midpoint impact categories, damage pathways and endpoint impact categories according to ReCiPe method, own illustration

Source: RIVM [39]

7. Life Cycle Inventory

The data used for LCI are listed in the following tables. In addition, figures of the model built are provided to transparently enhance the relationship between the data and processes within the model.

Regarding the input structure in SimaPro, it´s distinguished if inputs occur from (natural) resources, or from technosphere in form of material/fuels, electricity/heat, which is why it´s noted in the tables, see exemplarily Table 5. In the first row of a process the resulting output of the process is noted, i.e., product. In the rows underneath are the inputs from nature or technosphere listed. The column Allocation (%) is relevant for the products of a process. In case a product is fully allocated to another process, the allocation is set to 100 %. Otherwise, if the economic allocation is used, the corresponding percentage of the allocation is noted in the column. More detailed information on single processes is given in the text where it appears to be needed and if not already provided in yet introduced sections. Regarding the selection of generic processes, the country selection is focused on Austria, which is noted by *{AT}*. However, if no Austria-specific generic processes are available, an alternative country is selected that is considered similar to Austria, e.g., Switzerland *{CH}*. If no suitable alternative country is available or process on the preferred market is available, a process provided on the European market *{RER}* or a global process *{GLO}* is selected.

	Processes / Inputs / Outputs	Value	Unit	Alloc. (%)
Output:	***Product***			
Input from nature or technosphere:	***Resources***			
	Materials/fuels			
	Electricity/heat			

Table 5 Example for LCI structure

Source: Own listing

7.1 Biomass production

All data used for LCI for the core process biomass production are listed in Table 11 and all processes are shown in Figure 16.

7.1.1 Harvesting processes

For the motor-manual harvesting process, the generic process of *Power sawing, with catalytic converter {GLO}* is used. According to MÄSER [33], the hours of operation for two power saws is 0.003 h per reference flow. For the woodliner and liftliner harvesting processes, the generic process of 0.0949 MJ of *Diesel, burned in building machine* is used, since the specific machinery is not available in SimaPro. *Diesel, burned in building machine* represents the impact of diesel burned in any type of machine, and therefore is assumed to be a well replacement. The fuel consumption for woodliner and liftliner is reported by MÄSER [33]. In addition to the generic process of *Diesel, burned in building machine*, the woodliner process requires three power saws with a total operating time of 0.0002 hours, each per reference flow. The process liftliner also requires three power saws, with a total operating time of 0.0002 hours per reference flow and 0.0539 MJ per reference flow for the remaining components, represented as *Diesel, burned in building machine.*

In addition to the inputs from technosphere, each harvesting process is attributed with generic process of 1 kg *Wood, unspecified, standing/kg* as input from nature to represent the biomass feedstock.

The three different harvesting methods contribute differently to the total amount of biomass harvested, e.g., liftliner is the method that harvests the greatest amount of biomass. To reflect the different contributions per 1 kg woodchips W40, a weighting of the methods is applied based on data provided by MÄSER [33]. In doing so, the contributions of the harvesting methods to the total amount of biomass harvested within one harvesting period are calculated, see Table 6. The percentage is considered in Table 11.

Harvesting method	**Amount within one harvesting period**	**Percentage**
Motor-manual	936 kg/d	2 %
Woodliner	18,309 kg/d	36 %
Liftliner	31,077 kg/d	62 %
∑	50,322 kg/d	100 %

Table 6 Contribution of harvesting methods

Source: Own set up based on MÄSER [33]

7.1.2 Transportation processes

For the transportation of logs and woodchips by tractor and lorry, the generic processes of *Transport, tractor and trailer, agricultural {CH}* and *Transport, freight, lorry 16-32 metric ton, euro4 {RER}* are used. The calculation of transportation processes in the unit of ton-kilometer are based on MÄSER [33] and provided in Table 7.

Product	Locations	Distance	Mass	Ton-kilometer
Logs motor-manual	Within harvesting site	0.07 km	1 kg	$7*10^{-5}$ tkm
Logs transported lorry	From harvesting site to central place	15 km	1 kg	0.015 tkm
Logs transported tractor	From harvesting site to central place	15 km	1 kg	0.015 tkm
WC W40 transported lorry	From central place to storage bunker	5 km	1 kg	0.005 tkm
WC W40 transported tractor	From central place to storage bunker	5 km	1 kg	0.005 tkm
WC W15 transported tractor	From storage bunker to gasification plant	5 km	0.71 kg	0.0036 tkm

Table 7 Calculation of ton-kilometers for transport processes for core process biomass production

Source: Own calculation based on MÄSER [33]

7.1.3 Transition processes

For the transition at the storage bunker and at the gasification plant a wheel loader is used. Since no generic wheel loader process is available in SimaPro, the fuel consumption of the existing process is used and adopted to the generic process *Diesel, burned in building machine*.

The transition processes and their according fuel consumption is provided in Table 8. The calculations are based on the fuel consumptions reported by MÄSER [33].

Product	Transition location	Fuel consumption per 1 srm[3]	Result per 1 kg woodchips W40
WC W40 transitioned	Storage bunker (load off and on)	0.09 l	0.013 MJ
WC W15 transitioned	Gasification plant (load off)	0.0002 l	0.005 MJ

Table 8 Calculation of fuel consumption of transition processes for core process biomass production

Source: Own calculation based on MÄSER [33]

7.1.4 Chipping process

For the chipping of logs into woodchips, the generic process of *Wood chipping, chipper, mobile, diesel, at forest road {RER}*| *wood chipping, mobile chipper, at forest road* | *APOS, U* is used. The hours of operation, which are 0.00006 hr, are calculated based on data provided by MÄSER [33].

[3] The unit of 1 srm (German: “Schüttraummeter”) corresponds to 253 kg woodchips W40.

7.1.5 Drying I process

For the heat and electricity required to operate Drying I process, there´s no primary data available for the year 2020. Therefore, data from KÄPPLER [7] is taken and adapted to the current reference flow of 1 kg woodchips W40. Accordingly, 0.633 MJ per reference flow is required. The calculation is provided in Table 9.

Position	Value	Source
Reference flow, Käppler	3.706,416 kWh heat and electricity	KÄPPLER [7]
Heat required for Drying I per reference flow, Käppler	0.107 kWh per reference flow	KÄPPLER [7]
Heat required for Drying I total, Käppler	396,587 kWh	KÄPPLER [7]
Reference flow, current thesis	2.255,769 kg woodchips W40	ENERGIEWERK [34]
Heat required for Drying I per reference flow, current thesis	0.633 MJ per reference flow	Own calculation

Table 9 Calculation of heat required for Drying I process

Source: Own set up based on KÄPPLER [7] and ENERGIEWERK [34]

On-site, the heat required for this process is supplied by a biogas plant, which is operated by Energiewerk. However, this biogas plant is outside the scope in this assessment and a generic process of *Heat, central or small-scale, other than natural gas {AT} I heat and power co-generation, biogas, gas engine I APOS, U* is used as a substitute, that was also chosen by KÄPPLER [7].

Electricity is needed to operate the fans that circulate the warm air in the storage bunker and thus support the Drying I process. Since the generic process for the Austrian electricity country mix does not reflect the current electricity mix, the process has been adapted by increasing inputs of renewable energy components. The adjustments are based on the electricity mix, provided by STATISTA for 2019 [42] and are provided fully in the appendix. The data for the amount of electricity required is taken from KÄPPLER [7] and adopted to the current reference flow of 1 kg woodchips W40. Accordingly, 0.007 MJ per reference flow of electricity is required. The calculation is provided in Table 10.

Position	Value	Source
Reference flow, Käppler	3.706,416 kWh heat and electricity	KÄPPLER [7]
Electricity required for Drying I, Käppler	0.001 kWh per reference flow	KÄPPLER [7]
Electricity required for Drying I total, Käppler	4,007 kWh	KÄPPLER [7]
Reference flow, current thesis	2.255,769 kg woodchips W40	ENERGIEWERK [34]
Electricity required for Drying I per reference flow, current thesis	0.007 MJ per reference flow	Own calculation

Table 10 Calculation of electricity required for Drying I process

Source: Own set up based on KÄPPLER [7] and ENERGIEWERK [34]

Due to Drying I process and thus the reduction of water content of woodchips, water evaporates from the woodchips W40 and is released as an emission to air. The value considered as evaporating is the difference in weight between 1 kg woodchips W40 and 0.71 kg woodchips W15, i.e., 0.29 kg.

7.1.6 Constructions

Data for the construction of the storage bunker are adopted from KÄPPLER [7], see appendix.

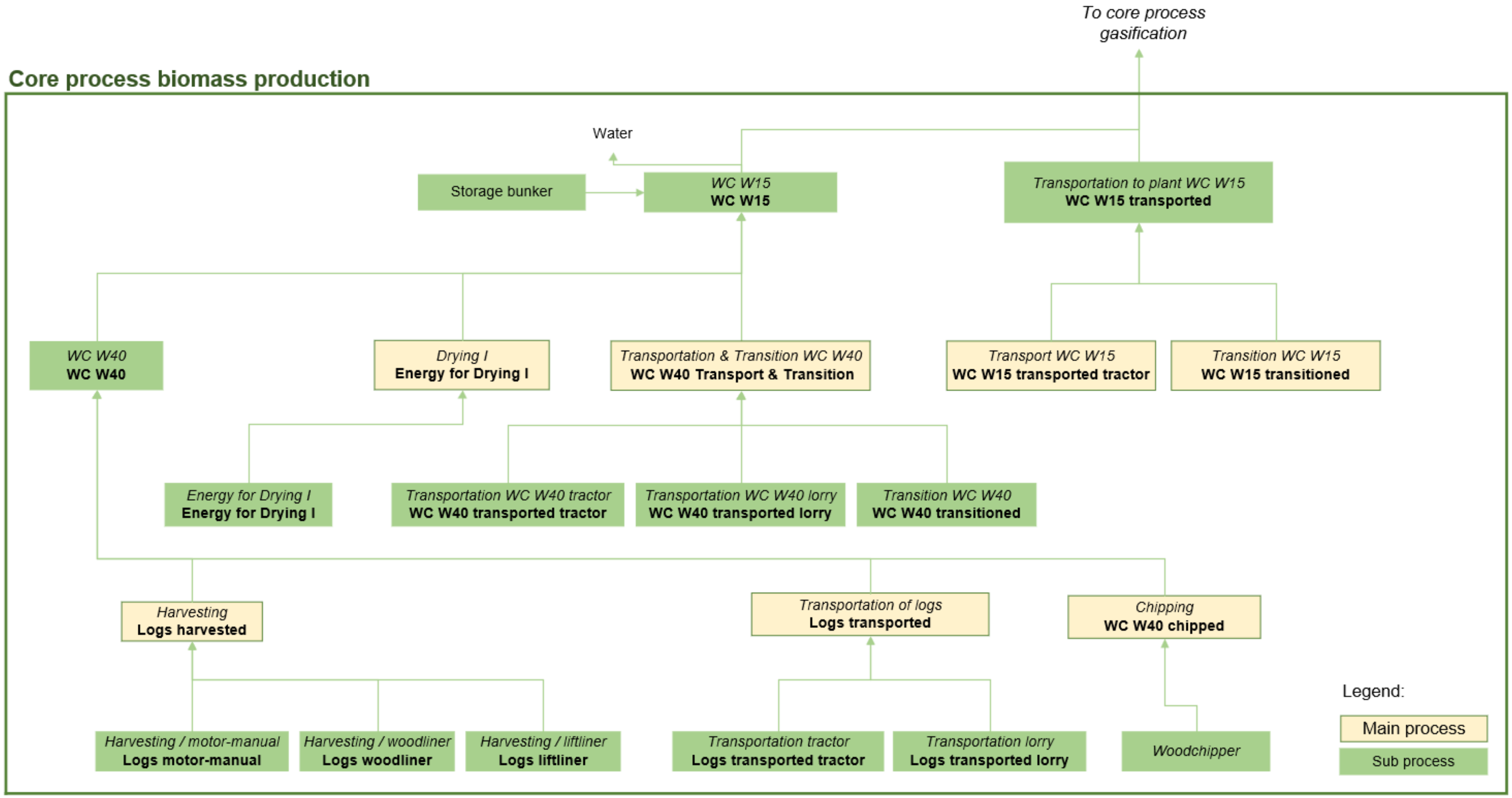

Figure 16 Core process of biomass production according to LCI
Source: Own illustration

Biomass production	Value	Unit	Alloc. (%)
Harvesting / motor-manual			
Products			
Logs motor-manual	1	kg	100
Resources			
Wood, unspecified, standing/kg	1	kg	
Materials/fuels			
Power sawing, with catalytic converter {GLO}| market for | APOS, U	0.003	hr	
Transport, tractor and trailer, agricultural {CH}| market for transport, tractor and trailer, agricultural | APOS, U	$7*10^{-5}$	tkm	
Harvesting / woodliner			
Products			
Logs woodliner	1	kg	100
Resources			
Wood, unspecified, standing/kg	1	kg	
Materials/fuels			
Diesel, burned in building machine {GLO}| market for | APOS, U	0.0949	MJ	
Power sawing, with catalytic converter {GLO}| market for | APOS, U	0.0002	hr	
Harvesting / liftliner			
Products			
Logs liftliner	1	kg	100
Resources			
Wood, unspecified, standing/kg	1	kg	
Materials/fuels			
Diesel, burned in building machine {GLO}| market for | APOS, U	0.0539	MJ	

Power sawing, with catalytic converter {GLO}| market for | APOS, U	0.0002	hr	
Harvesting			
Products			
Logs harvested	1	kg	100
Materials/fuels			
Logs motor-manual	0.02	kg	
Logs woodliner	0.36	kg	
Logs liftliner	0.62	kg	
Transportation by tractor			
Products			
Logs transported by tractor	1	kg	100
Materials/fuels			
Transport, tractor and trailer, agricultural {CH}| market for transport, tractor and trailer, agricultural | APOS, U	0.015	tkm	
Transportation by lorry			
Products			
Logs transported by lorry	1	kg	100
Materials/fuels			
Transport, freight, lorry 16-32 metric ton, euro4 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO4 | APOS, U	0.015	tkm	
Transportation of logs			
Products			
Logs transported	1	kg	100
Materials/fuels			
Logs transported by lorry	1	kg	

Logs transported tractor	1	kg	
Chipping			
Products			
WC W40 chipped	1	kg	100
Materials/fuels			
Wood chipping, chipper, mobile, diesel, at forest road {RER}| wood chipping, mobile chipper, at forest road | APOS, U	0.00006	hr	
WC W40			
Products			
WC W40	1	kg	100
Materials/fuels			
Logs harvested	1	kg	
WC W40 chipped	1	kg	
Logs transported	1	kg	
Transportation WC W40 tractor			
Products			
WC W40 transported tractor	1	kg	100
Materials/fuels			
Transport, tractor and trailer, agricultural {CH}| market for transport, tractor and trailer, agricultural | APOS, U	0.005	tkm	
Transportation WC W40 lorry			
Products			
WC W40 transported lorry	1	kg	100
Materials/fuels			
Transport, freight, lorry 3.5-7.5 metric ton, euro4 {RER}| market for transport, freight, lorry 3.5-7.5 metric ton, EURO4 | APOS, U	0.005	tkm	

Transition WC W40			
Products			
WC W40 transitioned	1	kg	100
Materials/fuels			
Diesel, burned in building machine {GLO}| market for | APOS, U	0.013	MJ	
Transport & Transition WC W40			
Products			
WC W40 Transport & Transition	1	kg	100
Materials/fuels			
WC W40 transitioned	2	kg	
WC W40 transported tractor	1	kg	
WC W40 transported lorry	1	kg	
Energy for Drying I			
Products			
Energy for Drying I	1	kg	100
Materials/fuels			
Heat, central or small-scale, other than natural gas {AT}| heat and power co-generation, biogas, gas engine | APOS, U	0.633	MJ	
Electricity, low voltage {AT}| market for | APOS, U I **ADJUSTED**	0.007	MJ	
WC W15			
Products			
WC W15	0.71	kg	100
Materials/fuels			
Energy for Drying I	1	kg	

WC W40 Transport & Transition	1	kg	
WC W40	1	kg	
Storage bunker	$1.48*10^{-8}$	p	
Emissions to air			
Water (evapotranspiration)	0.29	kg	
Transportation WC W15			
Products			
WC W15 transported tractor	0.71	kg	100
Materials/fuels			
Transport, tractor and trailer, agricultural {CH}| market for transport, tractor and trailer, agricultural | APOS, U	0.0036	tkm	
Transition WC W15			
Products			
WC W15 transitioned	0.71	kg	100
Materials/fuels			
Diesel, burned in building machine {GLO}| market for | APOS, U	0.005	MJ	
Transportation to plant WC W15			
Products			
WC W15 transported	0.71	kg	100
Materials/fuels			
WC W15 transported tractor	0.71	kg	
WC W15 transitioned	0.71	kg	

Table 11 LCI data for core process biomass production

Source: Own set up

7.2 Gasification

The core process gasification is summarized to the product 1 piece (p) *Gasification_dummy*, which corresponds to the conversion of 0.65 kg of woodchips W8 into 0.17 kg of biochar and 8.8 MJ of syngas. Here, 8.8 MJ of syngas reflects the accumulated energy obtained from the various processes in the core process energy production.

7.2.1 Energy for Drying II and for plant operation

For Drying II, heat from both the common busbar for heat on low temperature level as well as from the common busbar for heat on high temperature level is used. Based on data from ENERGIEWERK [34], 100,770 kWh of heat on low temperature level and 206,730 kWh of heat on high temperature level were used in 2020, which corresponds to 0.2 MJ per reference flow and 0.33 MJ per reference flow, respectively. As in Drying I, electricity for the fans to circulate the warm air is required. The data is taken from KÄPPLER [7] and adapted to the year of operation 2020. The amount of electricity required results in 0.0065 MJ per reference flow.

According to ENERGIEWERK [34], 204,846 kWh of electricity is required to operate the gasification plant itself in 2020, i.e., *Electricity demand Energiewerk*. This corresponds to 0.33 MJ per reference flow. For both electricity inputs, the adjusted electricity mix is used, which is provided in the appendix.

7.2.2 Constructions

Data for the construction of the main building and for the gasification system are adopted from KÄPPLER [7], see appendix.

7.2.3 Yields of biochar and syngas

According to ENERGIEWERK [34], a yield of 0.11 kg biochar W0 per reference flow was obtained in 2020. In addition to this yield, 0.06 kg of water is added, resulting in a total amount of 0.17 kg of biochar per reference flow, which is further used in the core process biochar use. Since there´s no generic process available for tap water for the Austrian market, the generic process on the Swiss market *Tap water {CH}| market for | APOS, U* is chosen instead. The gasification plant is located in ~ 5 km distance to Switzerland, the generic process chosen is therefore assumed to fit well.

To determine the amount of syngas, the amount of energy produced by the different processes was cumulated. This results in 8.8 MJ of syngas per reference flow.

Based on economic allocation, the product of 1 p of *Gasification_dummy* is allocated by 36 % and 64 % towards the following products *biochar* and *syngas*.

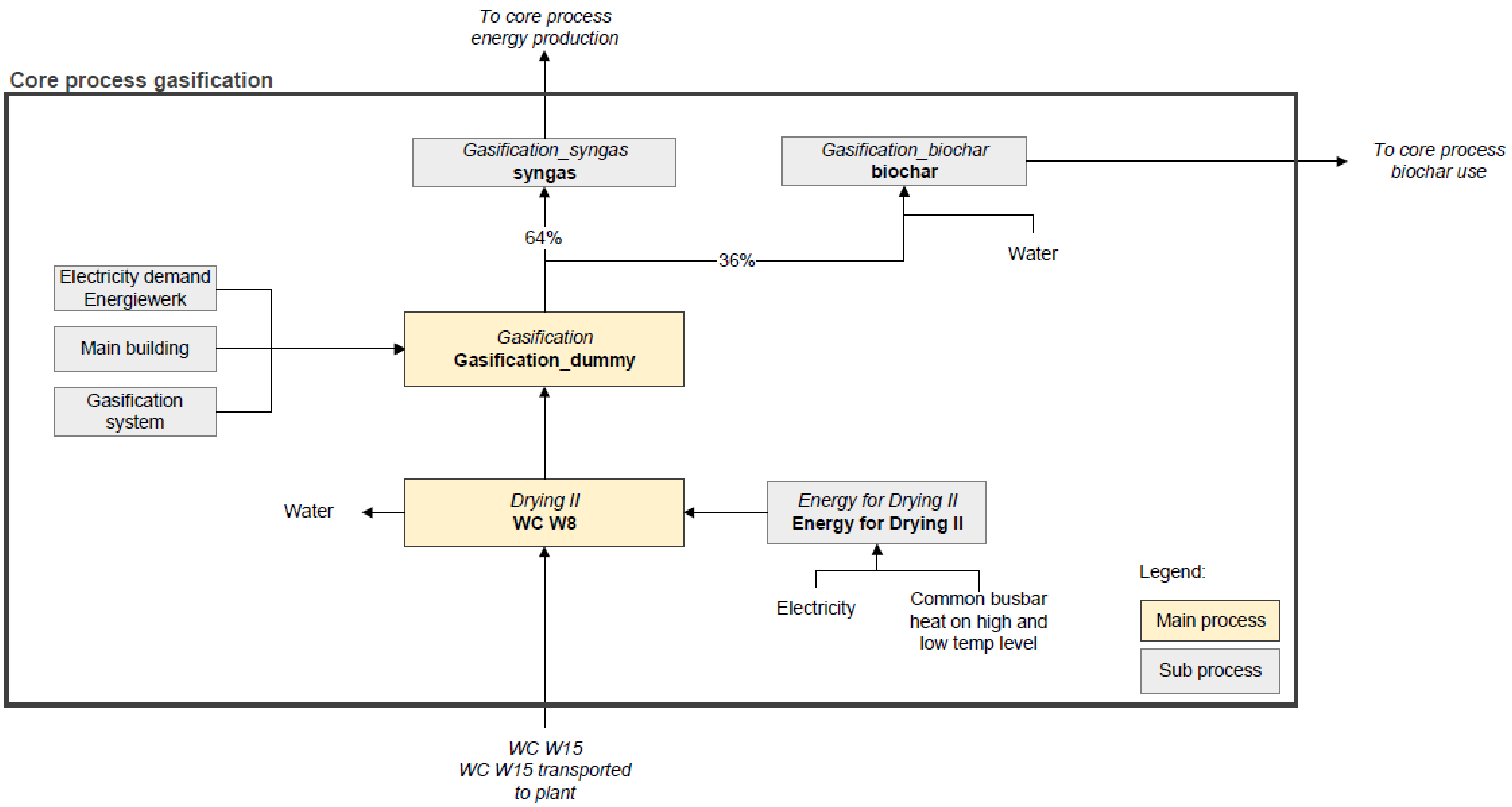

Figure 17 Core process of biomass production according to LCI
Source: Own illustration

Gasification	Value	Unit	Allocation (%)
Energy for Drying II			
Products			
Energy for Drying II	0.71	kg	100
Electricity/heat			
Common busbar heat low temp	0.2	MJ	
Common busbar heat high temp	0.33	MJ	
Electricity, low voltage {AT}| market for | APOS, U I **ADJUSTED**	0.0065	MJ	
Drying II			
Products			
WC W8	0.65	kg	100
Materials/fuels			
WC W15	0.71	kg	
Energy for Drying II	0.71	kg	
WC W15 transported to plant	0.71	kg	
Emissions to air			
Water (evapotranspiration)	0.06	kg	
Gasification			
Products			
Gasification_dummy	1	p	100
Materials/fuels			
WC W8	0.65	kg	
Gasification system	$2.19*10^{-8}$	p	
Main building	$1.1*10^{-8}$	p	

Electricity/heat			
Electricity, low voltage {AT}| market for | APOS, U I **ADJUSTED**	0.33	MJ	
Gasification_biochar			
Products			
Biochar	0.17	kg	100
Materials/fuels			
Gasification_dummy	0.36	p	
Tap water {CH}| market for | APOS, U	0.06	kg	
Gasification_syngas			
Products			
Syngas	8.8	MJ	100
Materials/fuels			
Gasification_dummy	0.64	p	

Table 12 LCI data for core process gasification

Source: Own set up

7.3 Energy production

7.3.1 Cooler

Due to economic allocation, the environmental impacts of the cooler, that includes all upstream processes, are allocated by 96 % towards 7.74 MJ of syngas that is further fed to the washer. The remaining 4 % is allocated towards 1.06 MJ of heat obtained from the cooler.

7.3.2 Washer

For the washer, 0.034 kg water is needed. After washing proceeded, 0.0001 m^3 water is drafted out of the washer process and treated as unpolluted wastewater being fed to wastewater treatment, for which the generic process of *Wastewater, unpolluted {CH}| market for wastewater, unpolluted | APOS, U* is chosen. According to the operator, the occurring wastewater has a quality that allows being treated as unpolluted. For the wastewater treatment, there´s only the generic process for the consideration of Switzerland available.

7.3.3 Gas flaring

For the combustion of syngas in the gas flaring, propane is used as an additive which is available as generic process that is *Propane {GLO}| market for | APOS, U*. On-site, the heat resulting from the gas flaring is not further used and therefore demonstrates a loss of heat. However, in the current model, the heat resulting from gas flaring is attributed towards the common busbar for heat on high temperature level and is therefore illustrated as a dashed line in Figure 19. This is modeled to have a cohesive energy balance.

7.3.4 Engine

Lubricating oil is needed to reduce wear on components of the gasification plant. The generic process chosen is *Lubricating oil {RER}| market for lubricating oil | APOS, U* with *{RER}* as indicator for the production of lubricating for the European market. On a regular basis, the lubricating oil is replaced, and the oil waste is given to final waste flow, so both amounts are 0.003 kg. The data for the construction of the CHP plant are adopted from KÄPPLER [7] and provided in the appendix. The data on emissions occurring due to combustion of the syngas were already provided in chapter 5.3.

7.3.5 Mixed cooler

For the mixed cooler, there are no additional inputs from nature or technosphere required. 0.24 MJ of heat on low temperature level is obtained and fed further towards the common busbar for heat on low temperature level.

7.3.6 Heat pump

As input from technosphere, a commercial heat pump is considered reflected by the generic process of *Heat pump, 30kW {GLO}| market for | APOS, U*. Further, electricity adjusted to the Austrian electricity mix as well as the input of heat on low temperature level from the common busbar for heat on low temperature are considered. The electricity required to operate the heat pump is calculated as followed:

Position	**Value**
Heat on high temp. level (Q_{out})	225,810 kWh
Electricity input ($W_{el.\ in}$)	55,957 kWh
COP ($Q_{out}/W_{el.\ in}$)	4.03
Heat on low temp. level (Q_{in}) ([1 - COP] * $W_{el.\ in}$)	169,853 kWh
Q_{in} per reference flow	0.27 MJ

Figure 18 Calculation of heat input for heat pump process

Source: Own set up based on data from ENERGIEWERK [34]

7.3.6.1 Common busbar heat low temperature

This process demonstrates the common busbar for heat on low temperature level. No additional inputs from nature or technosphere are required. 0.2 MJ of heat on low temperature level is fed towards Energy for Drying II process. The remaining 0.27 MJ per reference flow of heat on low temperature level is fed into the heat pump process.

7.3.6.2 Common busbar heat high temperature

This process demonstrates the common busbar for heat on high temperature level. In sum, 4.8 MJ of heat on high temperature level is fed into this process from different processes. 0.33 MJ of heat on high temperature is fed into Energy for Drying II process.

7.3.6.3 Common busbar heat high temperature with heating grid

The remaining 4.47 MJ of heat on high temperature level are fed to the district heating grid. The data for the construction of the heating grid is adopted from KÄPPLER [7], see appendix.

Core process energy production

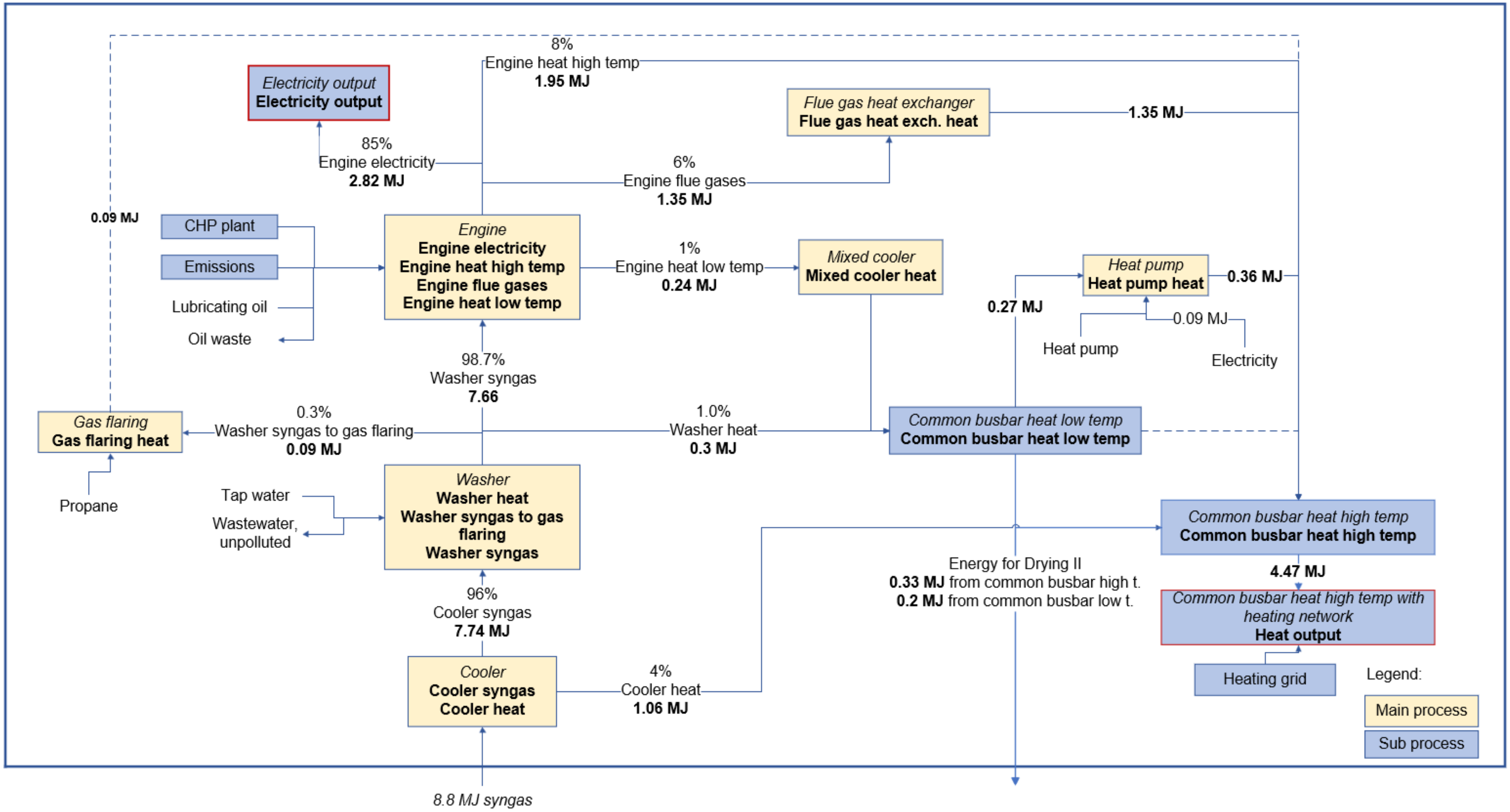

Figure 19 Core process of energy production according to LCI
Source: Own illustration

Energy production	Value	Unit	Allocation (%)
Cooler			
Products			
Cooler heat	1.06	MJ	4
Cooler syngas	7.74	MJ	96
Materials/fuels			
Syngas_gasification	8.8	MJ	
Washer			
Products			
Washer heat	0.3	MJ	1
Washer syngas to gas flaring	0.09	MJ	0.3
Washer syngas	7.74	MJ	98.7
Materials/fuels			
Cooler syngas	7.74	MJ	
Tap water {CH}| market for | APOS, U	0.034	kg	
Waste to treatment			
Wastewater, unpolluted {CH}| market for wastewater, unpolluted | APOS, U	0.0001	m^3	
Gas flaring			
Products			
Gas flaring heat	0.09	MJ	100
Materials/fuels			
Washer syngas to gas flaring	0.09	MJ	
Propane {GLO}| market for | APOS, U	0.00011	kg	
Engine			

Products			
Engine electricity	2.82	MJ	85
Engine heat high temp	1.95	MJ	8
Engine flue gases	1.35	MJ	6
Engine heat low temp	0.24	MJ	1
Materials/fuels			
Washer syngas	7.66	MJ	
CHP plant	$5.5*10^{-8}$	p	
Emissions	1	p	
Lubricating oil {RER}| market for lubricating oil | APOS, U	0.0003	kg	
Final waste flows			
Oil waste	0.0003	kg	
Emissions			
Products			
Emissions	1	p	100
Emissions to air			
Carbon dioxide, biogenic	0.791	kg	
Nitrogen dioxide, AT	9.6910^{-6}	kg	
Nitrogen monoxide	0.001046	kg	
Carbon monoxide, biogenic	0.000867	kg	
Nitrogen oxides, AT	0.001613	kg	
Mixed cooler			
Products			
Mixed cooler heat	0.24	MJ	100

Materials/fuels			
Engine heat low temp	0.24	MJ	
Common busbar heat low temp			
Products			
Common busbar heat low temp	0.54	MJ	100
Materials/fuels			
Washer heat	0.3	MJ	
Mixed cooler heat	0.24	MJ	
Heat pump			
Products			
Heat pump heat	0.36	MJ	100
Electricity/heat			
Heat pump, 30kW {GLO}| market for | APOS, U	$8.87*10^{-8}$	p	
Electricity, low voltage {AT}| market for | APOS, U I **ADJUSTED**	0.09	MJ	
Common busbar heat low temp	0.27	MJ	
Flue gas heat exchanger			
Products			
Flue gas heat exchanger heat	1.35	MJ	100
Materials/fuels			
Engine flue gases	1.35	MJ	
Common busbar heat high temp			
Products			
Common busbar heat high temp	4.8	MJ	100
Materials/fuels			

Cooler heat	1.06	MJ	
Flue gas heat exchanger heat	1.35	MJ	
Engine heat high temp	1.95	MJ	
Heat pump heat	0.36	MJ	
Gas flaring heat	0.09	MJ	
Common busbar heat high temp with heating network			
Products			
Common busbar heat high temp with heating network	4.47	MJ	100
Materials/fuels			
Common busbar heat high temp	4.47	MJ	
Heating Grid	$1.1*10^{-8}$	p	
Electricity output			
Products			
Electricity output	2.82	MJ	100
Materials/fuels			
Engine electricity	2.82	MJ	

Table 13 LCI data for core process energy production

Source: Own set up

7.4 Biochar use

7.4.1 Transportation to farm

According to MARTIN [36], the biochar is transported by a small lorry from the gasification plant to the farm, which is considered as the generic process of *Transport, freight, lorry 3.5-7.5 metric ton, euro5 {RER}| market for transport, freight, lorry 3.5-7.5 metric ton, EURO5 | APOS, U*. The ton-kilometres of 0.0034 tkm, results of 0.17 kg biochar transported over a distance of 20 km to the farm.

7.4.2 Application to soil

For the application to soil of both mixtures of solid and liquid manure and biochar, two generic processes are used which are *Solid manure loading and spreading, by hydraulic loader and spreader {CH}| processing | APOS, U* and *Liquid manure spreading, by vacuum tanker {CH}| processing | APOS, U*. The input data for these processes are based on the information provided by MARTIN [36] and are calculated as specific values, i.e., per 0.17 kg of biochar. As mentioned in chapter 5.5, one third of the biochar is applied to solid manure, which corresponds to 0.0567 kg. Furthermore, two-thirds of the biochar is applied to liquid manure, which is equivalent to 0.113 kg. The generic process of *Liquid manure spreading, by vacuum tanker {CH}| processing | APOS, U* requires the input data in the unit m^3, so 0.113 kg is converted to 0.00045 m^3 using the specified density of 250 kg/m^3 for biochar.

7.4.3 Manure treatment

The reduction of N_2O emissions is based on the amount of manure occurring: as KUPPER ET AL. [43] have reported, N_2O occurring from manure is relative to N contained in manure by 0.13 %. This results to an amount of 5.2 kg N_2O emissions, that is 0.13 % of 4,000 kg of N. As shown by CAYUELA ET AL. [6], a reduction of 27 % of N_2O emissions that occur from manure storage can be achieved by a mixing rate of 2 % of biochar and manure. This results in a total reduction of - 1.4 kg of N_2O emissions, that is equivalent to $-3.93 \cdot 10^{-5}$ kg per 0.17 kg biochar.

7.4.4 CO_2 sequestration

By applying biochar to soil, it is used as a long-term carbon storage, as the biochar is not undergoing any further thermochemical conversion. Therefore, the main process of soil application is attributed with negative biogenic CO_2 emissions. Only the carbon fraction of biochar (DM), i.e., 90 % is considered and here again only the stable fraction with CSF of 0.8, is considered. As biochar (DM) 0.11 kg per reference flow is obtained and therefore the stable carbon fraction is 0.0792 kg per reference flow. Converting 0.0792 kg of stable carbon fraction by 3.67, 0.291 kg CO_2 sequestration is obtained. This amount is considered as being previously absorbed from the atmosphere and therefore are accounted for as negative emissions.

The results for both, N_2O reduction and CO_2 sequestration are summarized in Table 14.

GHG	Reduction / Sequestration
N_2O	$- 3.93*10^{-5}$ kg/0.17 kg biochar
CO_2	- 0.291 kg/0.17 kg biochar

Table 14 Amount of CO_2 sequestration and reduction of N_2O considered for the use of biochar

Source: Own calculations

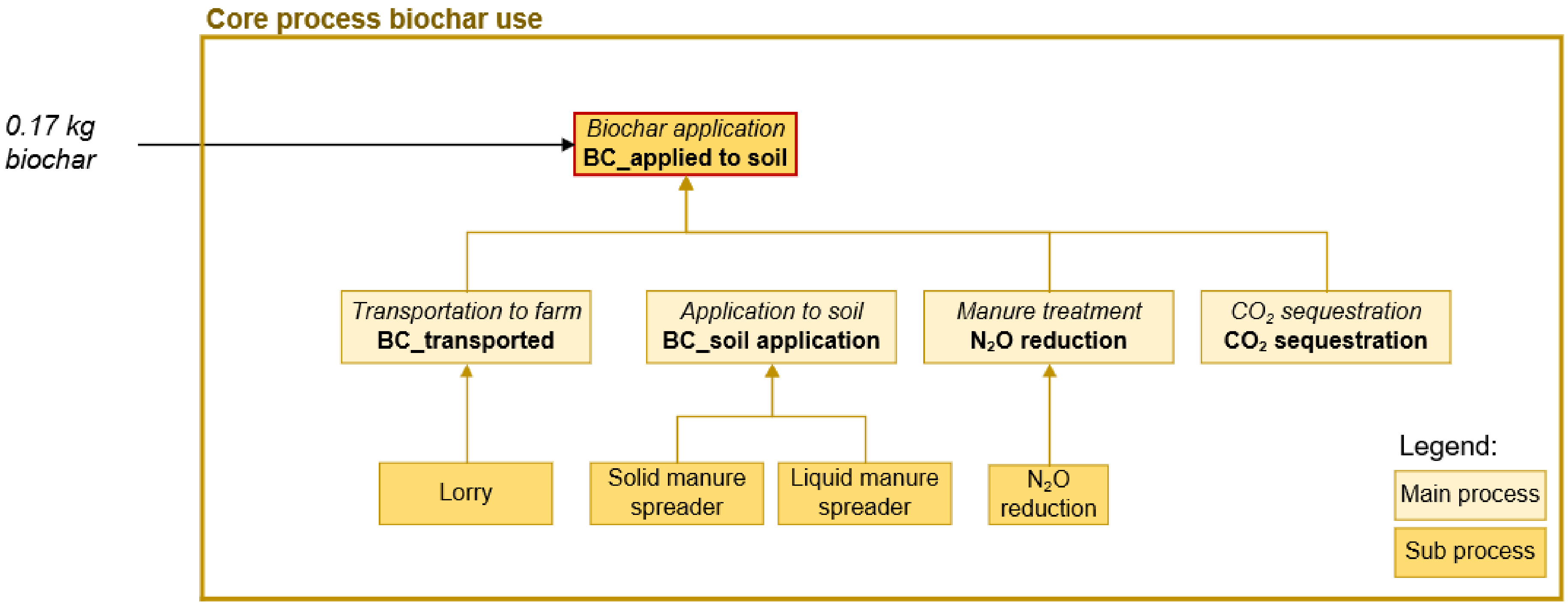

Figure 20 Core process of energy production according to LCI
Source: Own illustration

Biochar use	Value	Unit	Allocation (%)
Transportation to farm			
Products			
BC_transported	0.17	kg	100
Materials/fuels			
Transport, freight, lorry 3.5-7.5 metric ton, euro5 {RER}| market for transport, freight, lorry 3.5-7.5 metric ton, EURO5 | APOS, U	0.0034	tkm	
Application to soil			
Products			
BC_soil application	0.17	kg	100
Materials/fuels			
Solid manure loading and spreading, by hydraulic loader and spreader {CH}| processing | APOS, U	0.0567	kg	
Liquid manure spreading, by vacuum tanker {CH}| processing | APOS, U	0.000453	m^3	
CO_2 sequestration			
Products			
CO_2 sequestration	1	p	100
Emissions to soil			
Carbon dioxide, to soil or biomass stock	0.291	kg	
Manure treatment			
Products			
N_2O reduction	1	p	100
Emissions to air			
Dinitrogen monoxide	-0.000039	kg	
Biochar use			

Products			
BC applied to soil	0.17	kg	100
Materials/fuels			
BC transported to farm	0.17	kg	
Application to soil	0.17	kg	
Biochar	0.17	kg	
CO_2 sequestration	1	p	
N_2O reduced	1	p	

Table 15 LCI data on core process biochar use

Source: Own set up

8. Results

The environmental impacts of biochar, heat, and electricity from a wood gasification plant in Vorarlberg, Austria are evaluated by using the LCA method. Thereby, the core processes considered are biomass production, gasification, energy production, and biochar use. For the assessment of biochar, the amount of CO_2 sequestered and the reduction of N_2O due to manure treatment with biochar on the farm are of particular importance.

Based on the model and LCI, it´s possible to compute the environmental impacts for all core processes and their contributing main processes. Results are presented in the following sections. Thereby, the main processes correspond to the previously illustrated figures in chapter 7. The results for the two core processes of biomass production and gasification are presented together in a first step. All other results are presented towards the according functional units.

8.1 Biomass production and gasification

For the two core processes of biomass production and gasification, the calculation results in a GWP of 70.5*10 $^{-3}$ kg CO_{2eq} per 1 kg of woodchips W40 in total. The subtotals for the two core processes biomass production and gasification result in 47.6*10 $^{-3}$ kg CO_{2eq} and 22.8*10 $^{-3}$ kg CO_{2eq}, respectively, see Figure 21.

Within the core process biomass production, the main process *Chipping* is the most contributing process which results in a GWP of 16.6*10 $^{-3}$ kg CO_{2eq} per 1 kg woodchips W40. In contrast, the main process *Storage bunker* has the lowest impact on GWP and results in 1.6*10 $^{-3}$ kg CO_{2eq} per 1 kg woodchips W40. Comparing the main processes *Transportation of logs,* that is 7.9*10 $^{-3}$ kg CO_{2eq} per 1 kg woodchips W40, and *Transportation of WC W40*, that is 4.4*10 $^{-3}$ kg CO_{2eq} per 1 kg woodchips W40, leads to a higher result which correlates with the distances that were previously presented in Table 7. Further, the main processes *Energy for Drying I* and *Transition of WC W40* result in a GWP of 6.6*10 $^{-3}$ kg CO_{2eq} per 1 kg woodchips W40 and 2.4*10 $^{-3}$ kg CO_{2eq} per 1 kg woodchips W40, respectively.

For the core process gasification, the main process *Electricity demand Energiewerk* has the highest impact on GWP and results in 16.7*10 $^{-3}$ kg CO_{2eq} per 1 kg woodchips W40. The remaining main processes range between 0.5-1.5*10 $^{-3}$ kg CO_{2eq} per 1 kg woodchips W40. When comparing the main processes of transportation for the two core processes, the shorter distances lead to lower results on GWP for the core process gasification. Further, the main process *Energy for Drying II* process is lower than for the main process *Energy for Drying I* process. The results on GWP for the constructions in both core processes turn out to be very similar to each other.

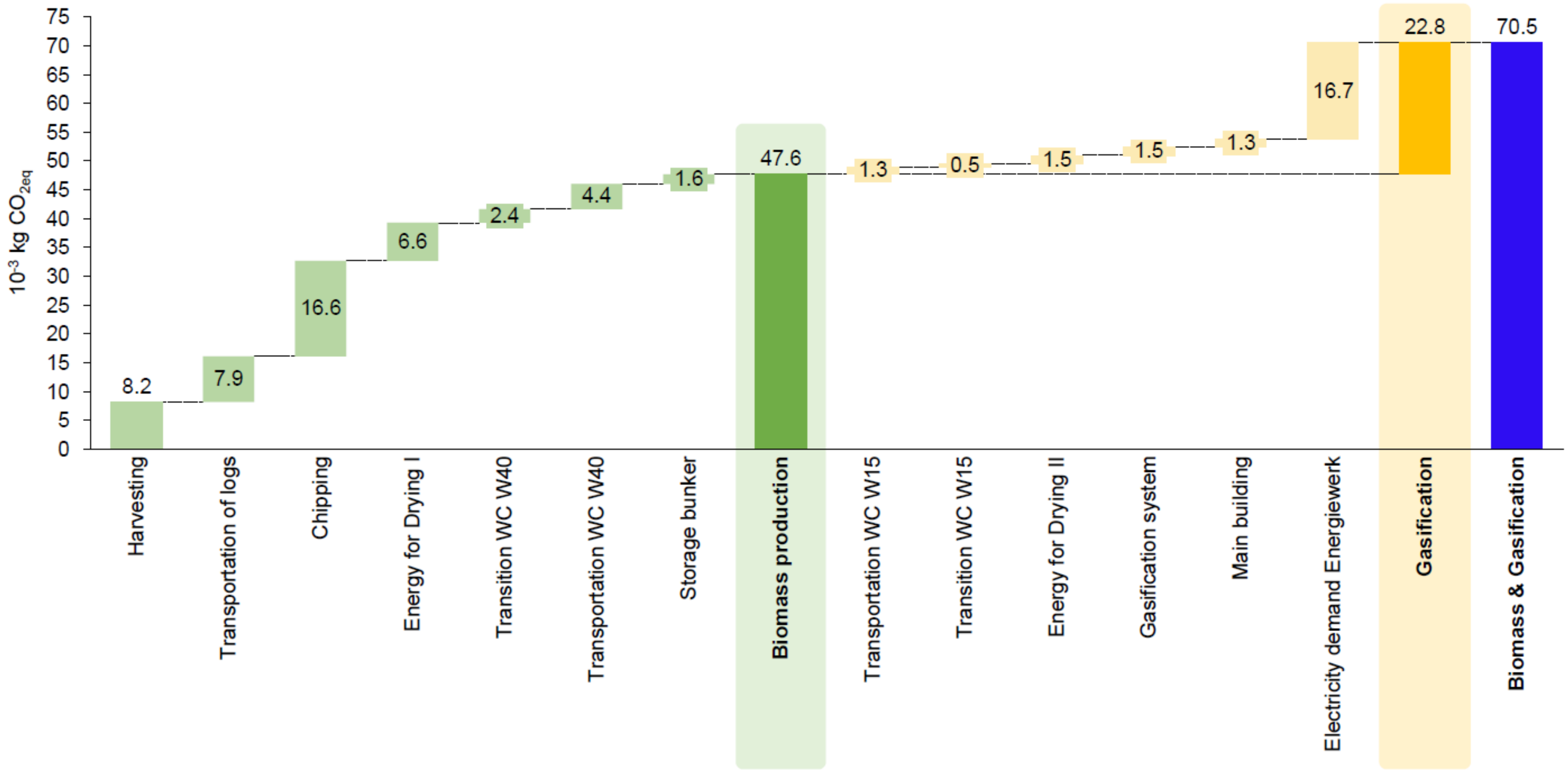

Figure 21 GWP for the core processes biomass production and gasification and contributing main and sub-processes
Source: Own illustration

The GWP of both core processes biomass production and gasification is allocated towards the following core processes of biochar use, i.e., 0.17 kg biochar, and energy production, i.e., 8.8 MJ syngas. The allocation is based on economic allocation and results in 36 %, which is equivalent to 25.4*10^{-3} kg CO_{2eq}, towards the core process of biochar use and in 64 %, which is equivalent to 45.1*10^{-3} kg CO_{2eq}, towards the core process of energy production, see Figure 22.

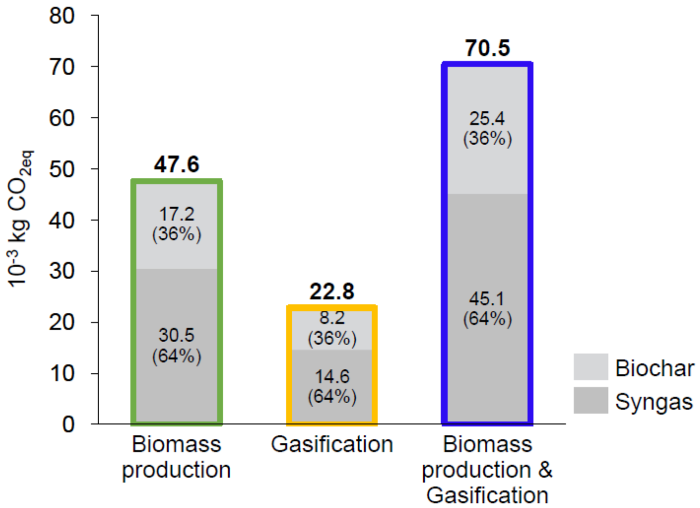

Figure 22 Allocation of the core processes biomass production and gasification towards the core processes biochar use and energy production

Source: Own illustration

The results on all midpoint impact categories for the main processes within the core process biomass production are presented in Figure 23 and for the main processes within the core process gasification in Figure 24. All results are presented with the factor of 10^{-3}. For the core process biomass production, the results for the midpoint impact categories Stratospheric ozone depletion, Freshwater eutrophication, and Marine eutrophication are 8.56*10^{-11}, 1.60*10^{-8}, and 3.84*10^{-9}, respectively. Moreover, for the core process gasification, the results for the midpoint impact categories Stratospheric ozone depletion, Freshwater eutrophication, and Marine eutrophication are 3.61*10^{-11}, 1.71*10^{-8}, and 1.43*10^{-9}, respectively.

All results for midpoint impact categories are provided in full in the appendix. An overview on the units corresponding to the midpoint impact categories is given in Table 16.

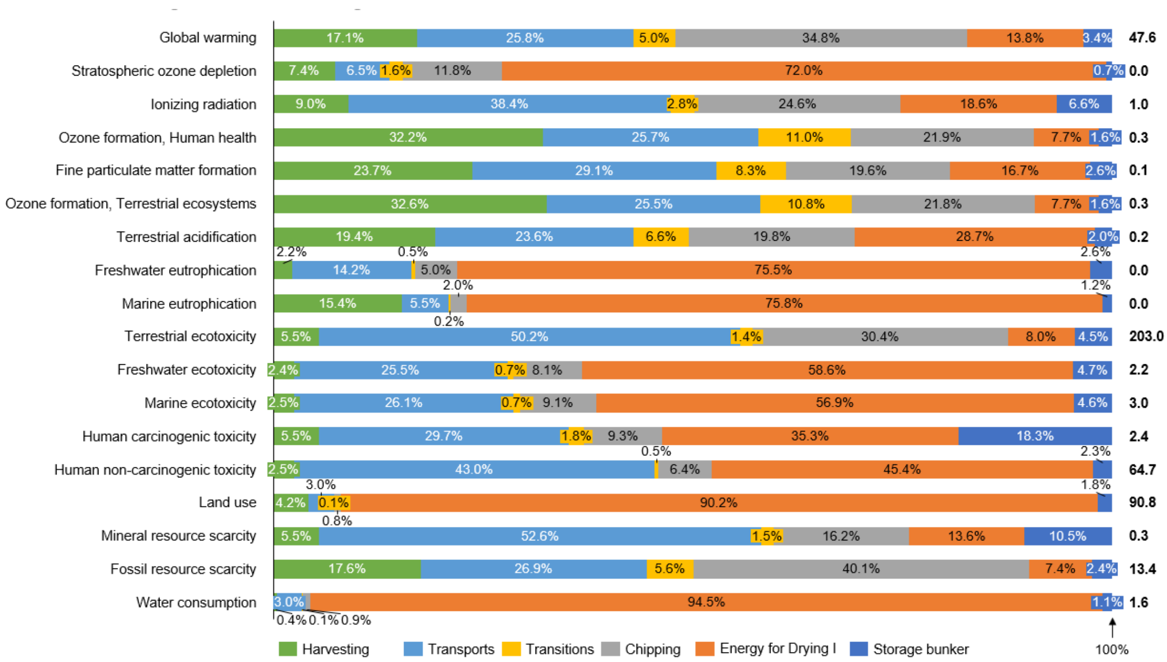

Figure 23 Results on all midpoint impact categories for the core process biomass production

Source: Own illustration

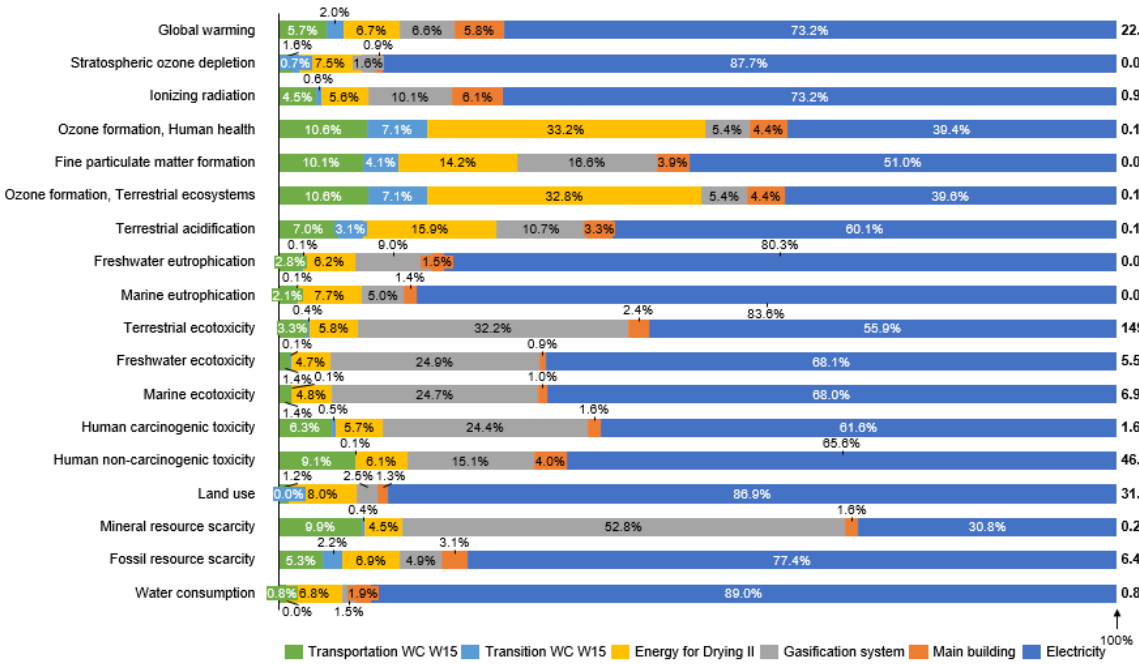

Figure 24 Results on all midpoint impact categories for the core process gasification

Source: Own illustration

Regarding the impacts at endpoint level, the damage to human health, ecosystems and resource availability, GWP of the core process gasification results in $6.54*10^{-8}$ DALY, $1.97*10^{-10}$ species.yr, and $5.39*10^{-15}$ species.yr, each per 1 p of gasification, that already includes the impacts of the core process biomass production. All results for the endpoint impact categories are provided in the appendix.

Impact category	**Unit**
Global warming	kg CO_{2eq}
Stratospheric ozone depletion	kg $CFC11_{eq}$
Ionizing radiation	kBq Co-60_{eq}
Ozone formation, Human health	kg NOx_{eq}
Fine particulate matter formation	kg $PM2.5_{eq}$
Ozone formation, Terrestrial ecosystems	kg NOx_{eq}
Terrestrial acidification	kg SO_{2eq}
Freshwater eutrophication	kg P_{eq}
Marine eutrophication	kg N_{eq}
Terrestrial ecotoxicity	kg 1,4-DCB
Freshwater ecotoxicity	kg 1,4-DCB
Marine ecotoxicity	kg 1,4-DCB
Human carcinogenic toxicity	kg 1,4-DCB
Human non-carcinogenic toxicity	kg 1,4-DCB
Land use	m^2a $crop_{eq}$
Mineral resource scarcity	kg Cu_{eq}
Fossil resource scarcity	kg oil_{eq}
Water consumption	m^3

Table 16 Units of midpoint impact categories

Source: Own set up adopted from [41]

8.2 Energy production

The previously determined result on GWP for syngas production, i.e., $45.1*10^{-3}$ kg CO_{2eq} per 1 kg woodchips W40, is allocated towards the main processes of the core process energy production. Within this core process, the processing of syngas eventually results in the combustion of syngas in the engine and heat and electricity are obtained from different main processes. The results on GWP for the main processes are presented in the following.

8.2.1 Heat on high temperature level

For the functional unit of heat on high temperature level, 4.74 MJ per 1 kg woodchips W40 is obtained, which results in a GWP of $17.1*10^{-3}$ kg CO_{2eq} and corresponds to $3.6*10^{-3}$ kg CO_{2eq} per 1 MJ.

The results for the main processes that contribute to the heat on high temperature level are presented in Figure 25. As to be seen, the process *Heat pump heat* is the most contributing process and results in a GWP of 5.5*10 $^{-3}$ kg CO_{2eq} per 1 kg woodchips W40. The second largest impact on GWP is the *Engine heat* process, which results in a GWP of 3.6*10 $^{-3}$ kg CO_{2eq} per 1 kg woodchips W40. Further, the impacts on GWP for the processes *Flue gas heat exchanger heat, Cooler heat* and *Gas flaring heat* result in 1.8*10 $^{-3}$ kg CO_{2eq}, 0.2*10 $^{-3}$ kg CO_{2eq} and 2.7*10 $^{-3}$ kg CO_{2eq}, each per 1 kg woodchips W40 respectively. The total amount of heat on high temperature level is fed to the *Common busbar of heat high temp.* which results in a GWP of 13.8*10 $^{-3}$ kg CO_{2eq} per 1 kg woodchips W40. A subtraction of 0.9*10 $^{-3}$ kg CO_{2eq} per 1 kg woodchips W40 is done for the heat on high temperature level which is fed to the *Energy for Drying II* process. The construction of the *Heating Grid* is additionally attributed, which results 4.2*10 $^{-3}$ kg CO_{2eq} per 1 kg woodchips W40. Therefore, the overall result for *Heat on high temp. level* is 17.1*10 $^{-3}$ kg CO_{2eq} per 1 kg woodchips W40. The results for all sub processes are provided in the appendix.

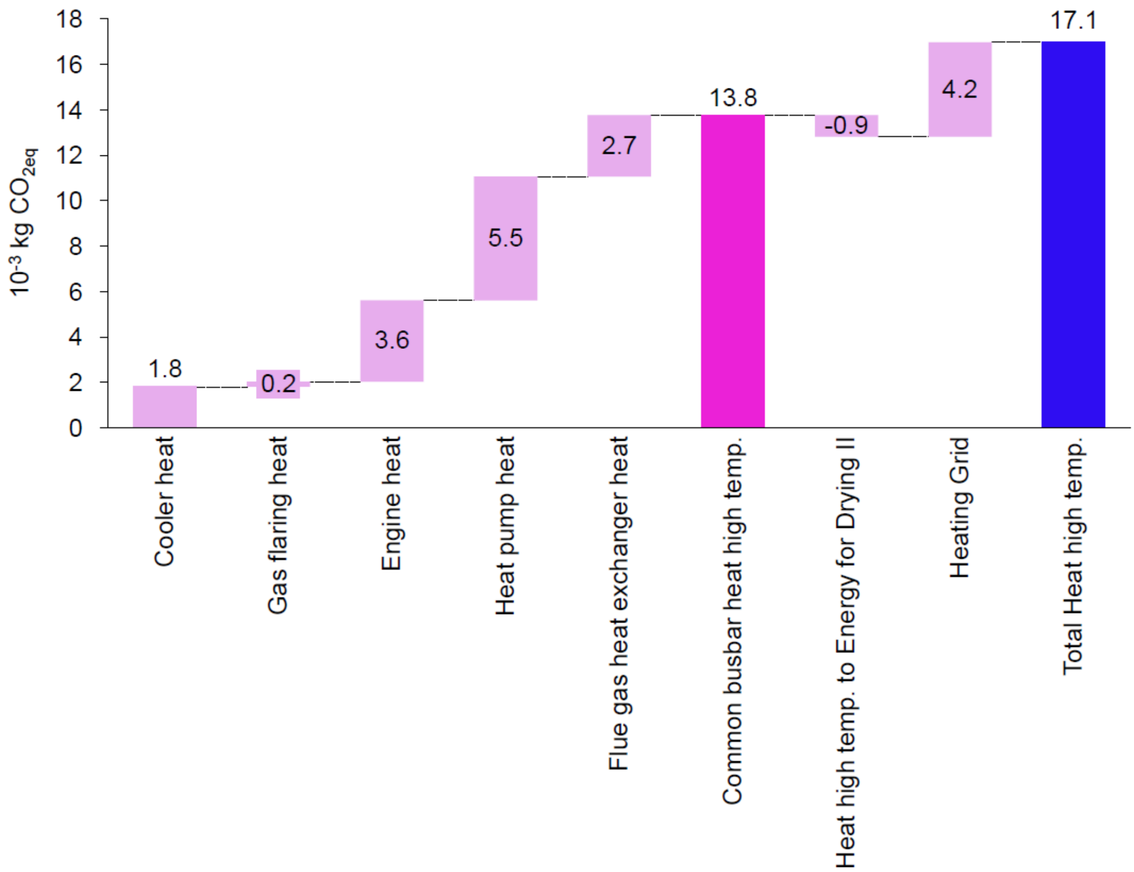

Figure 25 GWP for main processes contributing to the functional unit heat that is obtained from the core process energy production

Source: Own illustration

The results for all midpoint impact categories are shown in Figure 26 and provided in full in the appendix. Results are presented with the factor 10 $^{-3}$. For the midpoint impact categories of Stratospheric ozone depletion, Freshwater eutrophication, and Marine eutrophication the results are 3.12×10^{-12}, 7.09×10^{-10} and 1.35×10^{-10}, respectively. All units for the midpoint impact categories are presented in Table 16.

In Figure 26 the impact of heat on high temperature level which is fed to Drying II process is left out, so that the results presented are different compared to Figure 25 (in Figure 25 GWP results in 17.1×10^{-3} kg CO_{2eq} per 1 kg woodchips W40 whereas in Figure 26 the result for GWP is 18.0×10^{-3} kg CO_{2eq} per 1 kg woodchips W40).

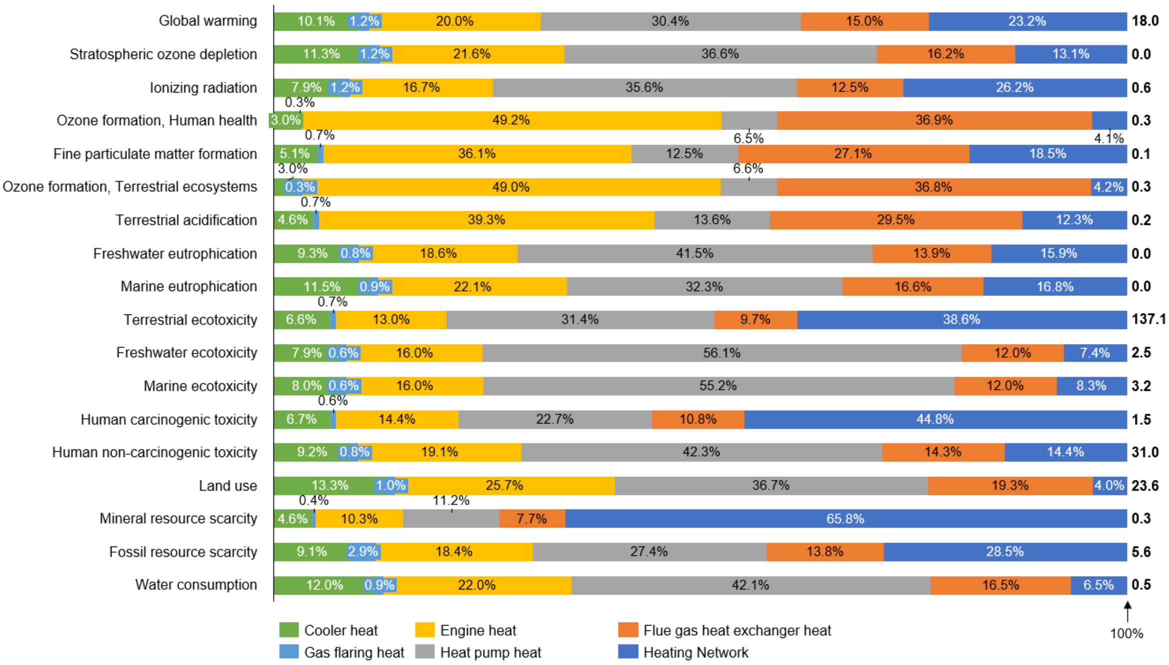

Figure 26 Results on all midpoints impact categories for functional unit of heat

Source: Own illustration

At endpoint level, the results on GWP on human health, terrestrial ecosystems and freshwater ecosystems are 1.58×10^{-8} DALY, 4.75×10^{-11} species.yr and 1.3×10^{-15} species.yr, each per 4.47 MJ of heat on high temperature level with heating network respectively. All results at endpoint level are presented in the appendix.

8.2.2 Electricity

For electricity, the functional unit of 2.82 MJ per 1 kg woodchips W40 is obtained, which results in a GWP of 38.1×10^{-3} kg CO_{2eq} per 1 kg woodchips W40. This corresponds to 13.5×10^{-3} kg CO_{2eq} per 1 MJ electricity.

As illustrated in Figure 27, the most contributing process towards the total result is *Washer syngas*, which contributes by 36.0×10^{-3} kg CO_{2eq} per 1 kg woodchips W40. However, this is not due to the washer process itself but to the upstream processes, i.e., the core processes of biomass production and gasification, that fed into the *Washer syngas* process. In addition, the process *Engine Electricity* contributes with a GWP of 2.2×10^{-3} kg CO_{2eq} per

1 kg woodchips W40. It´s referred to the appendix to get further information on the sub processes that are attributed towards the two main processes illustrated.

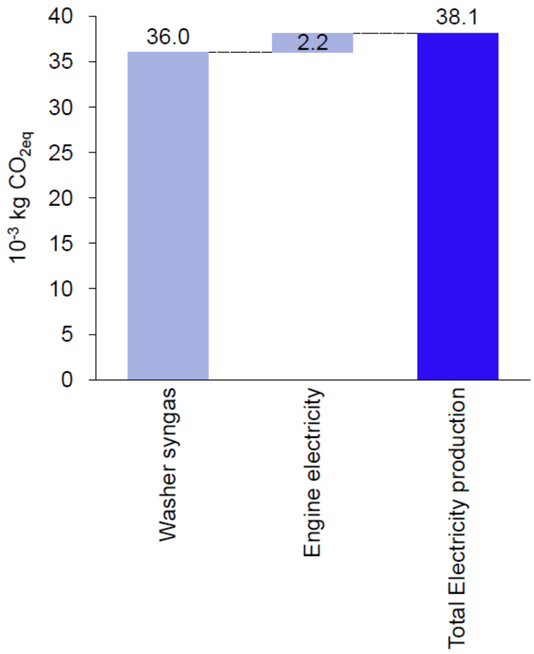

Figure 27 GWP for main processes contributing to functional unit of electricity
Source: Own illustration

Information on results for all further midpoint impact categories is provided in Figure 28, where total results are presented with the factor 10^{-3}. The results for the midpoint impact categories Stratospheric ozone depletion, Freshwater eutrophication and Marine eutrophication are $6.34*10^{-11}$, $1.51*10^{-8}$, and $2.76*10^{-9}$, respectively. For the units corresponding to all midpoints impact categories see Table 16.

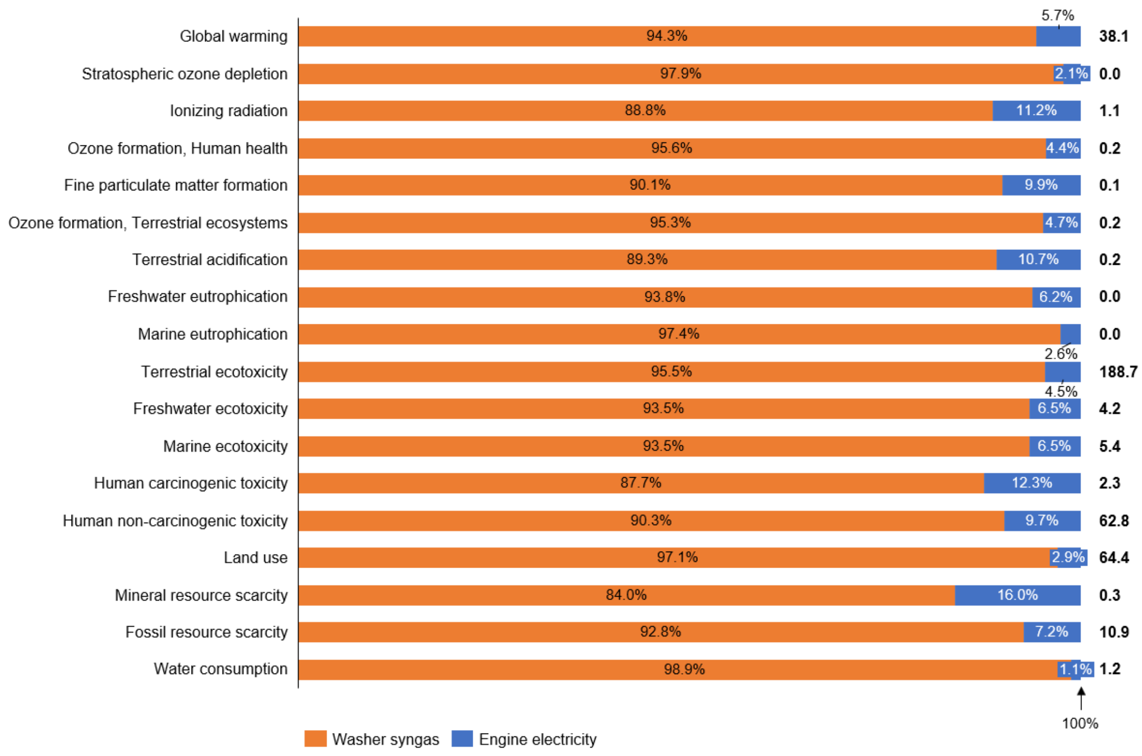

Figure 28 Results on all midpoint impact categories for the functional unit of electricity

Source: Own illustration

At endpoint level, the results for GWP on human health, terrestrial ecosystems and freshwater ecosystems are $3.5*10^{-8}$ DALY, $1.1*10^{-10}$ species.yr and $2.9*10^{-15}$ species.yr, each per 2.82 MJ of electricity respectively. All results at endpoint level are presented in the appendix.

8.3 Biochar use

For the functional unit of biochar, 0.17 kg of biochar per 1 kg woodchips W40 is obtained, which is used for manure treatment and applied to soil eventually. This results in a GWP of - $274.7*10^{-3}$ kg CO_{2eq} per 0.17 kg biochar, which is equivalent to $-1{,}616*10^{-3}$ kg CO_{2eq} per 1 kg (-1.6 kg CO_{2eq} per 1 kg biochar).

As to be seen in Figure 29, the main process of *CO_2 sequestration* is the most contributing process within the core process biochar use and results in a GWP of - $291.0*10^{-3}$ kg per 1 kg woodchips W40. Further, the upstream core processes of biomass production and gasification are allocated by 36 % towards the core process biochar use, i.e., *Biochar*, that is $25.4*10^{-3}$ kg CO_{2eq} per 1 kg woodchips W40 and therefore is the second most contributing process. The process *Manure treatment*, i.e., N_2O reduction, results in a negative GWP of - $11.6*10^{-3}$ kg CO_{2eq} per 1 kg woodchips W40. Further, the *Transport to farm* and the *Application to soil* have impacts of $1.8*10^{-3}$ kg CO_{2eq} and $0.8*10^{-3}$ kg CO_{2eq}, each per 1 kg woodchips W40 respectively. Again, it´s referred to the appendix for further information on sub processes.

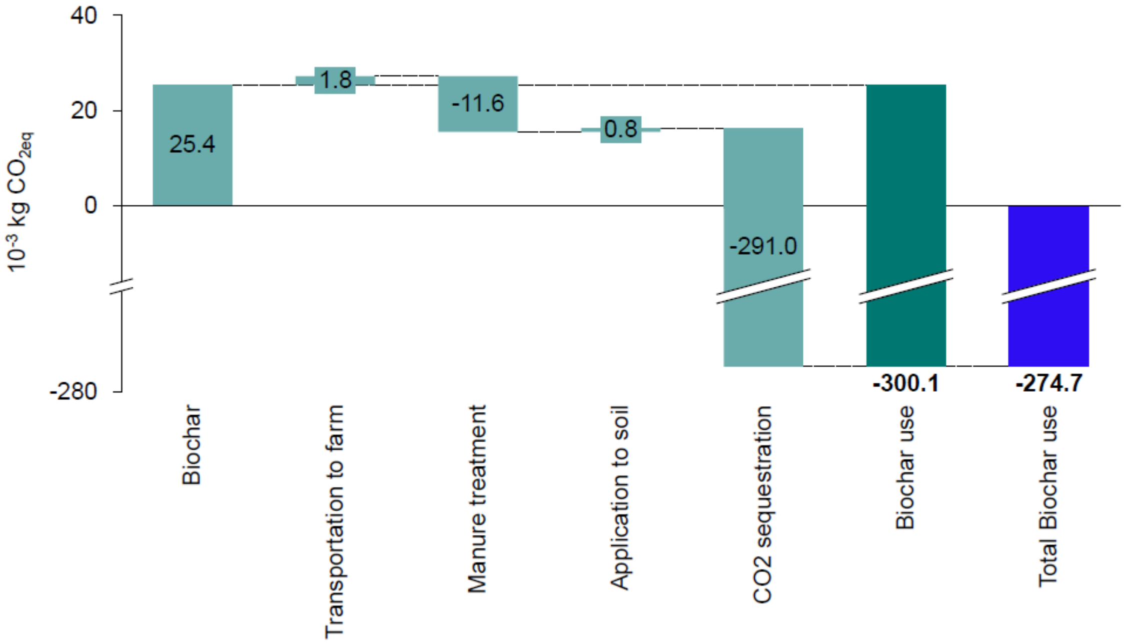

Figure 29 GWP for main processes contributing to the core process biochar use

Source: Own illustration

The results for all midpoint impact categories are presented in Figure 30. Thereby, total results are presented with the factor of 10^{-3}. The results for the midpoint impact categories Stratospheric ozone depletion, Fine particular matter formation, Freshwater eutrophication and Marine eutrophication are $3.84*10^{-10}$, $4.4*10^{-8}$, $1.03*10^{-8}$ and $1.93*10^{-9}$, respectively. For the units corresponding to all midpoints impact categories see Table 16.

As to be seen, the two midpoint impact categories GWP and Stratospheric ozone depletion both show negative results, that are mainly due to the upstream processes, represented as *Biochar*. The impact of upstream processes is also shown for the remaining midpoint impact categories. Further, both the impacts resulting from *CO_2 sequestration* and *Manure treatment* only contribute to the first two midpoint impact categories.

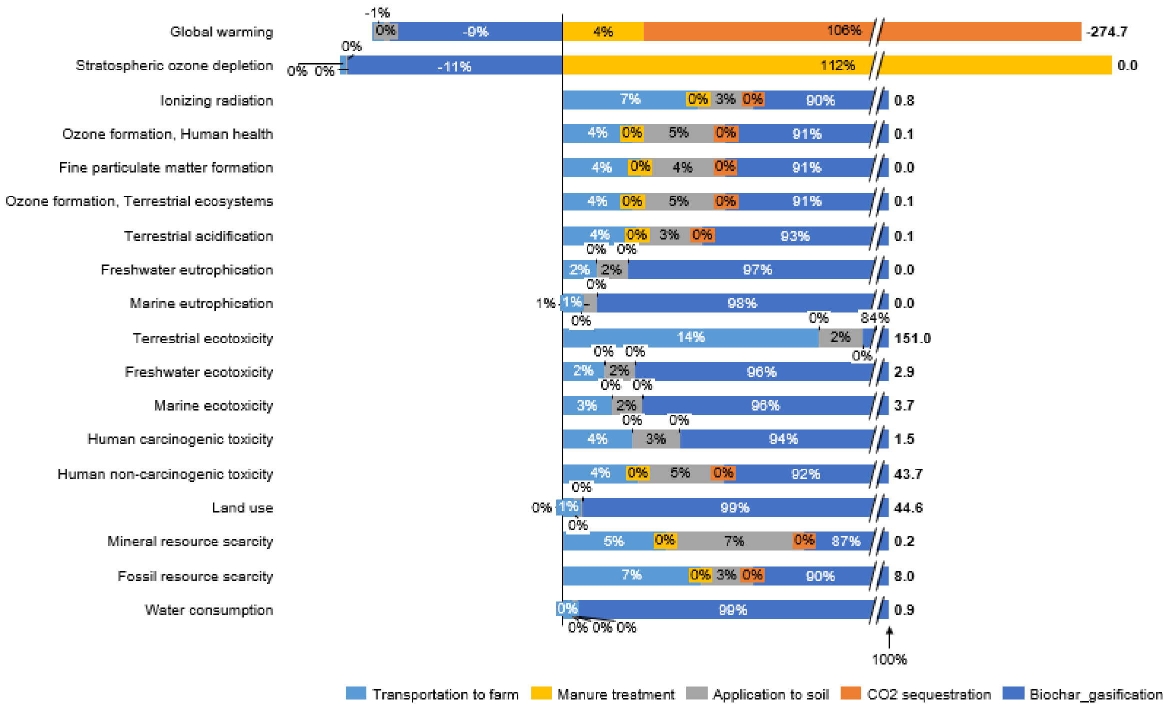

Figure 30 Results on midpoint impact categories for the main processes contributing to the core process biochar use

Source: Own illustration

At endpoint level, the results for global warming on human health, terrestrial ecosystems and freshwater ecosystems are -2.55*10 $^{-7}$ DALY, -7.69*10 $^{-10}$ species.yr and -2.10*10 $^{-14}$ species.yr, each per 0.17 kg of biochar applied to soil respectively. All results at endpoint level are presented in the appendix.

9. Discussion

The environmental impacts of biochar, heat and electricity from a wood gasification plant were assessed by using LCA method and the results obtained are discussed by different aspects in the following.

9.1 Scenario analysis

Different scenarios were tested on the model to see to what extent the results change. Four alternatives were therefore set up, which are:

- Scenario 1: use of the generic electricity country mix for Austria instead of the adjusted electricity mix.
- Scenario 2: use of energy allocation instead of economic allocation.
- Scenario 3: attributing the CO_2 sequestration potential to the harvesting process to allocate the effects of negative CO_2 emissions towards all functional units.

All three scenarios are compared to the Base-scenario, i.e., the already obtained results, provided in chapter 8.

The results are presented in Figure 31. As to be seen for results on scenario 1, slight increases of all results of all functional units are observed due to higher environmental impacts of the generic electricity mix for Austria. In case energy allocation is used, i.e., scenario 2, the GWP for the functional unit of heat has doubled, compared to the base-scenario. Whereas for the functional unit of electricity, the GWP has beneficially decreased compared to base-scenario. Only slight changes occur for the functional unit of biochar. The results on GWP in scenario 3 are in favor for the functional units of heat and electricity. Thereby, the CO_2 sequestration potential is allocated towards all functional units which leads to negative results for heat and electricity. As a consequence, the GWP for the functional unit of biochar increases.

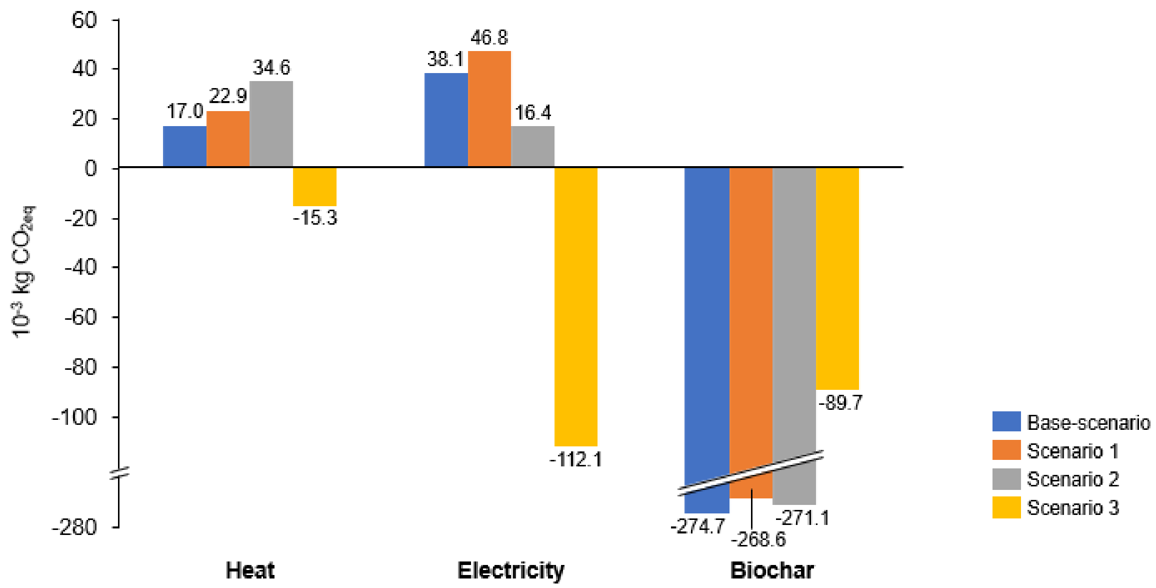

Figure 31 Comparison of results on GWP for heat and electricity (base-scenario and scenario 3) with literature

Source: Own illustration

9.2 Comparison of results on biochar

Comparing the results for the functional unit of biochar with literature, the result is within the range of the results from the literature, see Figure 32. Thereby, each result is converted to 1 kg biochar. It appears, that the result is closer to results of biochar produced from woody biomass, such as AZZI ET AL. [4], HAMEDANI ET AL. [17] and PUETTMANN ET AL. [23], than produced from manure, that is HAMEDANI ET AL. [17] or as a mixture of sewage sludge RAMACHANDRAN ET AL. [16]. The comparison thereby needs to be seen with respect to the limitations given in chapter 4, as there´s the variability on feedstock, functional unit or thermochemical conversion process. In Figure 32 it´s further distinguished between results that focus on biochar production and soil application or biochar production only, each color-coded.

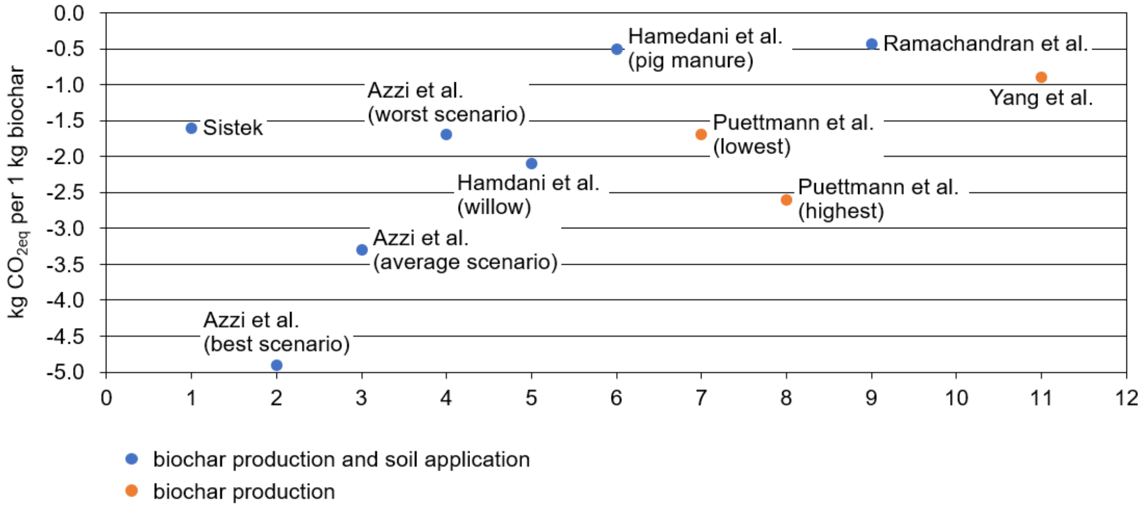

Figure 32 Comparison of the result on 1 kg biochar with literature
Source: Own illustration

9.3 Comparison of results on heat and electricity

The results for GWP for the functional units of heat and electricity obtained from base-scenario and scenario 3, see chapter 9.1, are compared to literature. The comparison of scenario 3 is chosen, since most studies reviewed consider the CO_2 sequestration potential for the functional units assessed. Each functional unit is converted to 1 MJ. An overview of the comparison with literature is shown in Figure 33. Here, the results obtained are close to the results from KÄPPLER [7]. As already mentioned, CARPENTIERI ET AL. [13] examined the effects of additional CO_2 removal during gasification which is considered to be the reason for the relatively strong differences to the current result. Further, RENO ET AL. [26] considered the production of methanol from bagasse combustion which could be the reason for the differences in results.

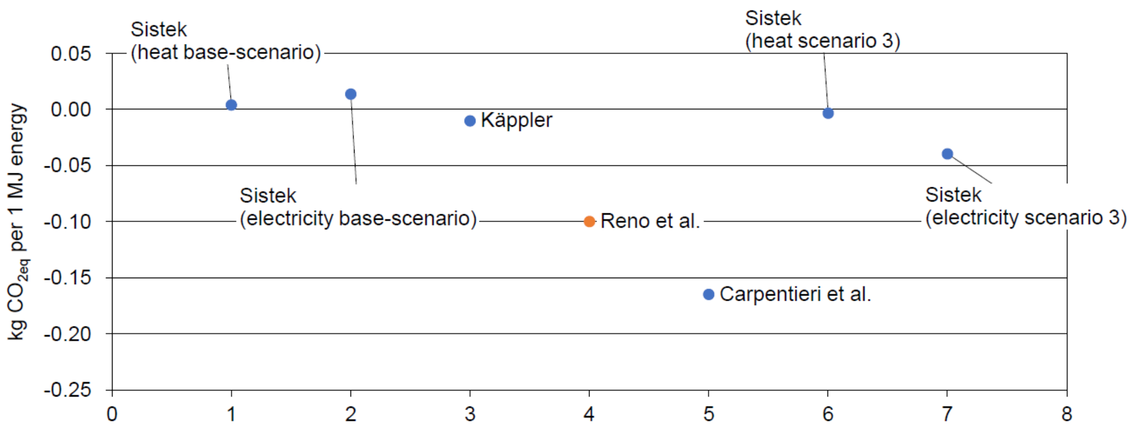

Figure 33 Comparison of results on 1 MJ heat and electricity, respectively
Source: Own illustration

9.4 Limitations of the study

9.4.1 Cut offs and assumptions

The assessment is limited at some points of the system. First, only the gasification system with the production of biochar, heat and electricity has been assessed. However, there are more energy production systems operated by Energiewerk Ilg that are linked to the assessed system, e.g., the biogas plant. At this point, a cut-off of the biogas plant has been made and a generic biogas plant process is chosen to provide the heat to operate the Drying I process instead. Further, the heat generated from the gas flaring process and the low temperature level heat that is not used by either Drying II or the heat pump are fed into the common busbar for heat on high temperature to ensure that all impacts are attributed within the system. However, on site, the heat from the gas flaring process is lost to the environment and the remaining heat at low temperature level is used for heating the rooms of the energy plant.

9.4.2 Data availability

As noted in LCI, not all data required for the assessment were available: regarding the core process of energy production, there were no data available for the composition of syngas components, i.e., syngas analysis, to calculate the amounts of emissions occurring due to combustion of syngas. Instead, a syngas analysis from a similar SynCraft gasification plant was used. Further, the calculation of emission components resulting from the combustion of syngas are based on an emission test carried out in April 2021. The measured values therefore do not match the operating year 2020 under consideration. Despite, the emissions calculated are not considered to be decisive towards the overall results on GWP, since they´re shown to have no impact on GWP as long as they´re considered as biogenic. Further, some data were missing regarding the amount of heat required as input for the heat pump process, and a simplified energy balance was fitted instead.

For the core process of biochar use and with regard to the N_2O reduction of manure, the calculations are based on the literature, as no on-farm data were available.

9.5 Trade-off potential of biochar

The biochar evaluated in this work has a LHV of 30,000 kJ/kg, i.e., 3,300 kJ per 0.11 kg biochar (DM), and thus represents a potential energy source and thus a trade-off for the CO_2 sequestration potential. As in the current thesis studied, biochar is used for soil application and cannot be used as energy source. As a consequence, less renewable energy from biomass is available and the use of fossil fuels could be used instead.

9.6 Conclusion

For the functional unit of 0.17 kg biochar applied to soil, calculations result in a GWP of - 274.7*10 $^{-3}$ kg CO_{2eq}, which corresponds to - 1.6 CO_{2eq} per 1 kg biochar applied to soil. Thereby, the effect of negative CO_2 emissions due to CO_2 sequestration potential of biochar was found to be crucial. The crediting of negative CO_2 emissions is only possible because a long-term carbon sink, that is soil, was chosen that prevents further thermochemical conversion of biochar, i.e., the release of biogenic CO_2 to the atmosphere. The reduction of N_2O emissions due to manure treatment with biochar points shows the optimization potential of biochar when used in cascade: it contributes to the total results for the functional unit of 0.17 kg biochar and is in favor of the total negative result on GWP.

For the functional unit of 4.74 MJ of heat on high temperature level, a total result for GWP of 17.1*10 $^{-3}$ kg CO_{2eq} is obtained, which is equivalent to 3.6*10 $^{-3}$ kg CO_{2eq} per 1 MJ. The most contributing process among the main processes for heat production is identified as the heat pump process, that has an impact of 5.5*10 $^{-3}$ kg CO_{2eq}. Emissions occurring due to the combustion of syngas in the engine were found to have no environmental impacts on GWP since they´re declared as biogenic emissions. Further, the functional unit of 2.82 MJ of electricity is obtained, that result in a GWP of 38.1*10 $^{-3}$ kg CO_{2eq}, that corresponds to 13.5*10 $^{-3}$ kg CO_{2eq} per 1 MJ. Here, the most contribution stems from the upstream processes of biomass production and gasification.

In summary, it was shown that the production and use of biochar in agriculture has the potential to contribute to the addressing of current climate challenges. The crucial potential was provided by the CO_2 sequestration potential by biochar, additionally the N_2O reduction potential by manure treatment. In particular, the allocation of the CO_2 sequestration potential influences the results of all functional units assessed, as shown by the scenario analysis. For further research, it is therefore recommended to enhance the question of the "right" allocation.

It´s assumed that this work addresses the interests of several groups: As for the LCA on biochar research community, this work contributes to the limited number of studies dealing with the production and use of biochar from gasification. Moreover, it is recommended to promote research regarding biochar from gasification processes and its use in practice. In doing so, it is considered important to reach out to end-user interests and audiences in order to link theory and practice. Attention needs to be paid to involve relevant stakeholders so that the scientifically based study results are sufficiently communicated in practice to achieve exploitation of the obtained results as well as further research. This seems particularly relevant, because the use of biochar is associated with other effects that have not been quantified: It has been shown that not all aspects during the life cycle of biochar can be translated into quantitative values, such as the reduction of odor occurring from manure observed by treating manure with biochar. In the future, it will be important to find a way to include the qualitative aspects, as these can also be considered crucial, especially when communicating with stakeholders from the field, who tend to focus on practical benefits rather than scientific findings. Also, in view of the possible legalization of feeding biochar to livestock in the medium and long term, it's assumed that the biochar market will undergo new developments that will emphasize its production and use. Besides the quantifiable and monetary aspects, the qualitative aspect of reducing the odor of manure can be decisive when it comes to the use of biochar. Meanwhile, there are several organizations and associations that deal with the production and standardization of biochar, such as the EBI. Such associations can use the results obtained for their public relations and lobbying work and show that the use of biochar not only has theoretical potential, but that an active use is already taking place which can be further promoted with the help of decision-makers, for example with regard to subsidies or regulatory frameworks.

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Appendix

Emissions occurring due to combustion of syngas

Results on midpoint impact categories

Results on endpoint impact categories

Economic and energy allocation

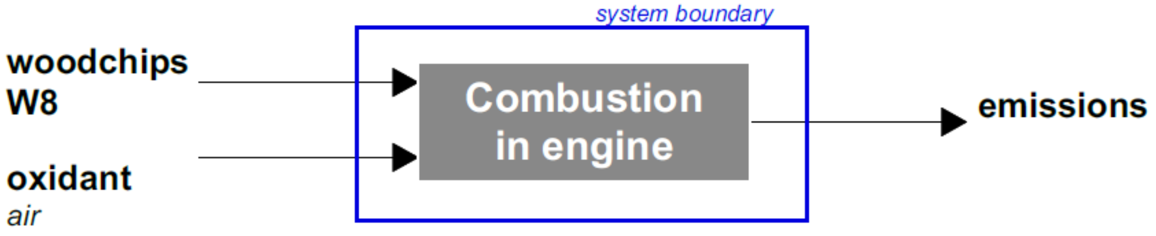
Adjustments of electricity mix

Constructions

Emissions occurring due to combustion of syngas

Combustion equation

To obtain the volumetric flow rate of fuel gas, the combustion of woodchips W8 is calculated since the data on the composition of syngas is not available. A sketch of the combustion is shown in the following figure.



In a first step, the volumetric flow rate of combustion air that is necessary for the combustion, is calculated. In a second step follows the calculation of the volumetric flow rate of flue gas, i.e., the combination of woodchips W8 and combustion air.

The following equation demonstrates the equation of basis combustion that serves as the starting point for the calculation:

$$\underbrace{C_aH_bO_cH_2O}_{\text{woodchips W8}} + \underbrace{\lambda d(O_2 + 3.76N_2)}_{\text{combustion air}} \rightarrow \underbrace{aCO_2 + bH_20 + (\lambda - 1)dO_2 + \lambda d * 3.76N_2}_{\text{flue gas}}$$

The coefficients $a - d$ correspond to mole of woodchips W8 properties and are provided in the column Mole (n) in the Appendix Table 1.

Component	**m (%)**	**Molar Mass (kg/kmol)**	**Mole (n)**
C	46.3	12	0.039 *(a)*
H	5.6	1	0.056 *(b)*
O	40.7	16	0.025 *(c)*
H_2O	8	18	0.004

Appendix Table 1

Source: Own calculation

Further, it is:

$d = a + \frac{b}{2} - \frac{c}{2}$;

$\lambda = 1.5$, based on emission test

Therefore, it is:

$d = 0.039 + \frac{0.056}{4} - \frac{0.025}{2} = 0.04$; $\lambda d = 1.5 * 0.04 = 0.06$

Therefore, the amount of combustion air required is

$(\lambda - 1)dO_2 + \lambda d * 3.76N_2 = 0.285\ kmol$

To now obtain the volumetric flow rate, the ideal gas equation is used, that is:

$$V = \frac{R * T * n}{p}$$

Where it is:

$R = 8.3145\ \frac{kJ}{kmol * K}$
$T = 298\ K$
$p = 100{,}000\ Pa$
$n = 0.285\ kmol$

Therefore, it is:

$V = 0.00705\ m^3$
$\boldsymbol{V = 7.05\ \frac{m^3}{kg_{fuel}}}$

Considering the amount of woodchips W8, that is 1.471,154 kg, the total volume of combustion air is:

$\boldsymbol{V_{total,combustion\ air} = 10.375{,}187\ m^3}$

Further, the coefficients of the flue gas are obtained:

Product component	**Mole (kmol)**
CO_2	0.039
H_2O	0.032
N_2	0.225
O_2	0.047
$\sum$	0.343

Appendix Table 2

Source: Own calculation

Using the ideal gas equation to obtain the volumetric flow rate of flue gas, with $n = 0.343$.

Therefore, it is:

$V = 0.00849\, m^3$

$V = 8.49\ \frac{m^3}{kg_{fuel}}$

$\boldsymbol{V_{total} = 12.484{,}921\ m^3}$

The emission test is based on dry flue gas, which requires the subtraction of water contained in the flue gas. The volume for water contained in the flue gas with $n = 0.032$, is:

$\boldsymbol{V_{total,H_2O} = 1.182{,}635\ m^3}$

By subtraction of $V_{total} - V_{total,H_2O}$, the total volume of flue gas without water is:

$\boldsymbol{V_{total} = 11.302{,}285\ m^3}$

Further, using the known volumetric flow rate of dry flue gas, the actual amount of emissions according to the reference flow can be calculated. First, results on emissions measured by the emission test are listed in the table above. The results thereby are referred to 5 % of O_2 contained in the emission flow rate. However, the actual amount of O_2 measured during the emission test is 7 % which is why the emissions need to be transformed by using the following equation [44]. The results for the adjusted emissions are listed as well in the table above.

$$E_{mea} = \frac{21\,\% - 7\,\%}{21\,\% - O_{ref}} * E_{ref}$$

Where it is:

E_{mea} = Emission component measured

O_{ref} = Oxygen reference, which corresponds to 5 %

E_{ref} = Emission component measured corresponding to O_{ref}

Results on midpoint impact categories

Product:	1 kg Logs harvested (of project Biochar)				
Method:	ReCiPe 2016 Midpoint (H) V1.04 / World (2010) H				
Indicator:	Characterisation				
Impact category	Unit	Total	logs motor-manual	logs woodliner	logs liftliner
Global warming	kg CO2 eq	0,00816976	0,000468408	0,003681987	0,004019363
Stratospheric ozone depletion	kg CFC11 eq	6,29E-09	6,17E-10	2,59E-09	3,09E-09
Ionizing radiation	kBq Co-60 eq	8,72E-05	3,71E-06	4,05E-05	4,29E-05
Ozone formation, Human health	kg NOx eq	8,51E-05	2,28E-06	4,08E-05	4,20E-05
Fine particulate matter formation	kg PM2.5 eq	1,92E-05	4,26E-07	9,28E-06	9,46E-06
Ozone formation, Terrestrial ecosystems	kg NOx eq	8,86E-05	2,83E-06	4,21E-05	4,37E-05
Terrestrial acidification	kg SO2 eq	3,87E-05	1,03E-06	1,86E-05	1,91E-05
Freshwater eutrophication	kg P eq	3,58E-07	3,41E-08	1,48E-07	1,75E-07
Marine eutrophication	kg N eq	5,90E-07	1,34E-07	1,70E-07	2,86E-07
Terrestrial ecotoxicity	kg 1,4-DCB	0,01111962	0,000841189	0,00481713	0,005461305
Freshwater ecotoxicity	kg 1,4-DCB	5,49E-05	3,28E-06	2,46E-05	2,70E-05
Marine ecotoxicity	kg 1,4-DCB	7,57E-05	4,07E-06	3,44E-05	3,72E-05
Human carcinogenic toxicity	kg 1,4-DCB	0,00013039	4,45E-06	6,17E-05	6,43E-05
Human non-carcinogenic toxicity	kg 1,4-DCB	0,00160709	0,000195829	0,000625768	0,000785489
Land use	m2a crop eq	0,00380095	0,00086117	0,001097481	0,001842296
Mineral resource scarcity	kg Cu eq	1,44E-05	1,04E-06	6,29E-06	7,08E-06
Fossil resource scarcity	kg oil eq	0,00236648	9,62E-05	0,001104289	0,001165971
Water consumption	m3	6,73E-06	4,49E-07	2,97E-06	3,31E-06

Product:	1 kg Logs transported (of project Biochar)			
Method:	ReCiPe 2016 Midpoint (H) V1.04 / World (2010) H			
Impact category	Unit	Total	Logs transported by lorry	Logs transported by tractor
Global warming	kg CO2 eq	0,0079144	0,00248428	0,00543012
Stratospheric ozone depletion	kg CFC11 eq	3,59E-09	1,15E-09	2,44E-09
Ionizing radiation	kBq Co-60 eq	0,00023241	5,94E-05	0,00017306
Ozone formation, Human health	kg NOx eq	4,60E-05	1,14E-05	3,47E-05
Fine particulate matter formation	kg PM2.5 eq	1,62E-05	3,08E-06	1,31E-05
Ozone formation, Terrestrial ecosystems	kg NOx eq	4,70E-05	1,16E-05	3,54E-05
Terrestrial acidification	kg SO2 eq	3,17E-05	7,37E-06	2,43E-05
Freshwater eutrophication	kg P eq	1,54E-06	1,80E-07	1,36E-06
Marine eutrophication	kg N eq	1,43E-07	1,76E-08	1,26E-07
Terrestrial ecotoxicity	kg 1,4-DCB	0,06506201	0,04452965	0,02053236
Freshwater ecotoxicity	kg 1,4-DCB	0,00037314	5,69E-05	0,00031625
Marine ecotoxicity	kg 1,4-DCB	0,00050936	9,84E-05	0,00041095
Human carcinogenic toxicity	kg 1,4-DCB	0,0004792	5,27E-05	0,00042646
Human non-carcinogenic toxicity	kg 1,4-DCB	0,01938276	0,00181344	0,01756932
Land use	m2a crop eq	0,00187198	0,00027499	0,00159699
Mineral resource scarcity	kg Cu eq	9,42E-05	8,93E-06	8,53E-05
Fossil resource scarcity	kg oil eq	0,00228179	0,00085519	0,0014266
Water consumption	m3	3,14E-05	4,36E-06	2,71E-05

Product:	1 kg WC W40 (of project Biochar)					
Method:	ReCiPe 2016 Midpoint (H) V1.04 / World (2010) H					
Impact category	Unit	Total	Logs harvested	WC W40 chipped	Logs transported	
Global warming	kg CO2 eq	0,03266697	0,00816976	0,016582816	0,0079144	
Stratospheric ozone depletion	kg CFC11 eq	2,00E-08	6,29E-09	1,01E-08	3,59E-09	
Ionizing radiation	kBq Co-60 eq	0,00055745	8,72E-05	0,000237862	0,00023241	
Ozone formation, Human health	kg NOx eq	0,00018891	8,51E-05	5,78E-05	4,60E-05	
Fine particulate matter formation	kg PM2.5 eq	5,11E-05	1,92E-05	1,58E-05	1,62E-05	
Ozone formation, Terrestrial ecosystems	kg NOx eq	0,00019482	8,86E-05	5,92E-05	4,70E-05	
Terrestrial acidification	kg SO2 eq	0,00011003	3,87E-05	3,96E-05	3,17E-05	
Freshwater eutrophication	kg P eq	2,69E-06	3,58E-07	7,90E-07	1,54E-06	
Marine eutrophication	kg N eq	8,10E-07	5,90E-07	7,57E-08	1,43E-07	
Terrestrial ecotoxicity	kg 1,4-DCB	0,13794305	0,01111962	0,06176142	0,06506201	
Freshwater ecotoxicity	kg 1,4-DCB	0,00061025	5,49E-05	0,000182232	0,00037314	
Marine ecotoxicity	kg 1,4-DCB	0,00085756	7,57E-05	0,000272507	0,00050936	
Human carcinogenic toxicity	kg 1,4-DCB	0,00083043	0,00013039	0,000220846	0,0004792	
Human non-carcinogenic toxicity	kg 1,4-DCB	0,02512861	0,00160709	0,004138762	0,01938276	
Land use	m2a crop eq	0,00636516	0,00380095	0,00069223	0,00187198	
Mineral resource scarcity	kg Cu eq	0,0001512	1,44E-05	4,26E-05	9,42E-05	
Fossil resource scarcity	kg oil eq	0,01002988	0,00236648	0,005381607	0,00228179	
Water consumption	m3	5,24E-05	0	6,73E-06	1,42E-05	3,14E-05

Product:	1 kg Energy for Drying I (of project Biochar)			
Method:	ReCiPe 2016 Midpoint (H) V1.04 / World (2010) H			
Impact category	Unit	Total	Heat, central or small-scale, other than natural gas {AT}| heat and power co-generation, biogas, gas engine | APOS, U	Electricity, low voltage {AT}| market for | APOS, U I ADJUSTED
Global warming	kg CO2 eq	0,00658631	0,00623211	0,0003542
Stratospheric ozone depletion	kg CFC11 eq	6,16E-08	6,10E-08	6,72E-10
Ionizing radiation	kBq Co-60 eq	0,00017968	0,00016522	1,45E-05
Ozone formation, Human health	kg NOx eq	2,04E-05	1,98E-05	6,56E-07
Fine particulate matter formation	kg PM2.5 eq	1,34E-05	1,31E-05	3,35E-07
Ozone formation, Terrestrial ecosystems	kg NOx eq	2,08E-05	2,02E-05	6,73E-07
Terrestrial acidification	kg SO2 eq	5,73E-05	5,63E-05	1,06E-06
Freshwater eutrophication	kg P eq	1,21E-05	1,19E-05	2,00E-07
Marine eutrophication	kg N eq	2,91E-06	2,88E-06	2,53E-08
Terrestrial ecotoxicity	kg 1,4-DCB	0,01615582	0,01437877	0,00177705
Freshwater ecotoxicity	kg 1,4-DCB	0,00131234	0,00123236	8,00E-05
Marine ecotoxicity	kg 1,4-DCB	0,00170783	0,00160899	9,88E-05
Human carcinogenic toxicity	kg 1,4-DCB	0,00083585	0,00081448	2,14E-05
Human non-carcinogenic toxicity	kg 1,4-DCB	0,0293453	0,02869877	0,00064653
Land use	m2a crop eq	0,08189825	0,0813124	0,00058586
Mineral resource scarcity	kg Cu eq	3,58E-05	3,44E-05	1,35E-06
Fossil resource scarcity	kg oil eq	0,00099665	0,00089074	0,0001059
Water consumption	m3	0,00147945	0,00146417	1,53E-05

Product:	1 kg WC W40 Transport & Transition (of project Biochar)				
Method:	ReCiPe 2016 Midpoint (H) V1.04 / World (2010) H				
Impact category	Unit	Total	WC W40 transitioned	WC W40 transported lorry	WC W40 transported tractor
Global warming	kg CO2 eq	0,006751868	0,002374814	0,002567016	0,001810038
Stratospheric ozone depletion	kg CFC11 eq	3,35E-09	1,41E-09	1,13E-09	8,13E-10
Ionizing radiation	kBq Co-60 eq	0,00016574	2,75E-05	8,06E-05	5,77E-05
Ozone formation, Human health	kg NOx eq	5,08E-05	2,90E-05	1,02E-05	1,16E-05
Fine particulate matter formation	kg PM2.5 eq	1,40E-05	6,68E-06	2,98E-06	4,36E-06
Ozone formation, Terrestrial ecosystems	kg NOx eq	5,17E-05	2,95E-05	1,05E-05	1,18E-05
Terrestrial acidification	kg SO2 eq	2,87E-05	1,32E-05	7,38E-06	8,11E-06
Freshwater eutrophication	kg P eq	8,02E-07	8,19E-08	2,65E-07	4,55E-07
Marine eutrophication	kg N eq	7,62E-08	7,53E-09	2,68E-08	4,19E-08
Terrestrial ecotoxicity	kg 1,4-DCB	0,039834013	0,002899545	0,03009035	0,006844119
Freshwater ecotoxicity	kg 1,4-DCB	0,000213373	1,58E-05	9,22E-05	0,000105416
Marine ecotoxicity	kg 1,4-DCB	0,00029701	2,25E-05	0,000137541	0,000136983
Human carcinogenic toxicity	kg 1,4-DCB	0,000267841	4,29E-05	8,28E-05	0,000142152
Human non-carcinogenic toxicity	kg 1,4-DCB	0,008694085	0,000298889	0,002538756	0,00585644
Land use	m2a crop eq	0,000935672	4,89E-05	0,000354441	0,00053233
Mineral resource scarcity	kg Cu eq	4,77E-05	3,85E-06	1,54E-05	2,84E-05
Fossil resource scarcity	kg oil eq	0,002082552	0,00075265	0,000854368	0,000475535
Water consumption	m3	1,69E-05	1,86E-06	6,03E-06	9,02E-06

Product:	0,71 kg WC W15 (of project Biochar)					
Method:	ReCiPe 2016 Midpoint (H) V1.04 / World (2010) H					
Impact category	Unit	Total	Energy for Drying I	WC W40 Transport & Transition	WC W40	Storage bunker
Global warming	kg CO2 eq	0,04764741	0,00658631	0,00675187	0,03266697	0,00164226
Stratospheric ozone depletion	kg CFC11 eq	8,56E-08	6,16E-08	3,35E-09	2,00E-08	6,04E-10
Ionizing radiation	kBq Co-60 eq	0,00096653	0,00017968	0,00016574	0,00055745	6,37E-05
Ozone formation, Human health	kg NOx eq	0,00026428	2,04E-05	5,08E-05	0,00018891	4,12E-06
Fine particulate matter formation	kg PM2.5 eq	8,07E-05	1,34E-05	1,40E-05	5,11E-05	2,12E-06
Ozone formation, Terrestrial ecosystems	kg NOx eq	0,00027164	2,08E-05	5,17E-05	0,00019482	4,26E-06
Terrestrial acidification	kg SO2 eq	0,00020005	5,73E-05	2,87E-05	0,00011003	3,99E-06
Freshwater eutrophication	kg P eq	1,60E-05	1,21E-05	8,02E-07	2,69E-06	4,14E-07
Marine eutrophication	kg N eq	3,84E-06	2,91E-06	7,62E-08	8,10E-07	4,55E-08
Terrestrial ecotoxicity	kg 1,4-DCB	0,20302074	0,01615582	0,03983401	0,13794305	0,00908785
Freshwater ecotoxicity	kg 1,4-DCB	0,00224035	0,00131234	0,00021337	0,00061025	0,00010439
Marine ecotoxicity	kg 1,4-DCB	0,00299903	0,00170783	0,00029701	0,00085756	0,00013663
Human carcinogenic toxicity	kg 1,4-DCB	0,0023685	0,00083585	0,00026784	0,00083043	0,00043438
Human non-carcinogenic toxicity	kg 1,4-DCB	0,0646545	0,0293453	0,00869409	0,02512861	0,00148651
Land use	m2a crop eq	0,0907967	0,08189825	0,00093567	0,00636516	0,00159762
Mineral resource scarcity	kg Cu eq	0,00026217	3,58E-05	4,77E-05	0,0001512	2,76E-05
Fossil resource scarcity	kg oil eq	0,01343531	0,00099665	0,00208255	0,01002988	0,00032623
Water consumption	m3	0,00156565	0,00147945	1,69E-05	5,24E-05	1,69E-05

Product:	0,71 kg WC W15 transported to plant (of project Biochar)			
Method:	ReCiPe 2016 Midpoint (H) V1.04 / World (2010) H			
Impact category	Unit	Total	WC W15 transported tractor	WC W15 transitioned
Global warming	kg CO2 eq	0,00175992	0,001303228	0,0004567
Stratospheric ozone depletion	kg CFC11 eq	8,56E-10	5,85E-10	2,71E-10
Ionizing radiation	kBq Co-60 eq	4,68E-05	4,15E-05	5,28E-06
Ozone formation, Human health	kg NOx eq	1,39E-05	8,32E-06	5,58E-06
Fine particulate matter formation	kg PM2.5 eq	4,42E-06	3,14E-06	1,28E-06
Ozone formation, Terrestrial ecosystems	kg NOx eq	1,42E-05	8,50E-06	5,67E-06
Terrestrial acidification	kg SO2 eq	8,38E-06	5,84E-06	2,54E-06
Freshwater eutrophication	kg P eq	3,43E-07	3,27E-07	1,57E-08
Marine eutrophication	kg N eq	3,16E-08	3,02E-08	1,45E-09
Terrestrial ecotoxicity	kg 1,4-DCB	0,00548537	0,004927765	0,0005576
Freshwater ecotoxicity	kg 1,4-DCB	7,89E-05	7,59E-05	3,03E-06
Marine ecotoxicity	kg 1,4-DCB	0,00010295	9,86E-05	4,32E-06
Human carcinogenic toxicity	kg 1,4-DCB	0,0001106	0,00010235	8,25E-06
Human non-carcinogenic toxicity	kg 1,4-DCB	0,00427412	0,004216637	5,75E-05
Land use	m2a crop eq	0,00039268	0,000383278	9,40E-06
Mineral resource scarcity	kg Cu eq	2,12E-05	2,05E-05	7,40E-07
Fossil resource scarcity	kg oil eq	0,00048713	0,000342385	0,00014474
Water consumption	m3	6,85E-06	6,49E-06	3,57E-07

Product:	0,71 kg Energy for Drying II (of project Biochar)	
Method:	ReCiPe 2016 Midpoint (H) V1.04 / World (2010) H	
Impact category	Unit	Energy for Drying II
Global warming	kg CO2 eq	0,00153616
Stratospheric ozone depletion	kg CFC11 eq	2,72E-09
Ionizing radiation	kBq Co-60 eq	5,21E-05
Ozone formation, Human health	kg NOx eq	2,61E-05
Fine particulate matter formation	kg PM2.5 eq	4,40E-06
Ozone formation, Terrestrial ecosystems	kg NOx eq	2,62E-05
Terrestrial acidification	kg SO2 eq	1,32E-05
Freshwater eutrophication	kg P eq	7,29E-07
Marine eutrophication	kg N eq	1,10E-07
Terrestrial ecotoxicity	kg 1,4-DCB	0,0087357
Freshwater ecotoxicity	kg 1,4-DCB	0,00026287
Marine ecotoxicity	kg 1,4-DCB	0,00032834
Human carcinogenic toxicity	kg 1,4-DCB	9,32E-05
Human non-carcinogenic toxicity	kg 1,4-DCB	0,00284515
Land use	m2a crop eq	0,0025487
Mineral resource scarcity	kg Cu eq	9,25E-06
Fossil resource scarcity	kg oil eq	0,00044809
Water consumption	m3	5,49E-05

Product:	1 piece Gasification (of project Biochar)					
Method:	ReCiPe 2016 Midpoint (H) V1.04 / World (2010) H					
Impact category	Unit	Total	W8	Gasification system	Main building	Electricity
Global warming	kg CO2 eq	0,070467807	0,050943495	0,00149852	0,001327587	0,016698206
Stratospheric ozone depletion	kg CFC11 eq	1,2172E-07	8,91769E-08	5,74188E-10	3,0973E-10	3,16591E-08
Ionizing radiation	kBq Co-60 eq	0,00189773	0,001065431	9,4022E-05	5,64002E-05	0,000681877
Ozone formation, Human health	kg NOx eq	0,000342899	0,000304263	4,20954E-06	3,48526E-06	3,09411E-05
Fine particulate matter formation	kg PM2.5 eq	0,000111691	8,95261E-05	5,14691E-06	1,21036E-06	1,58079E-05
Ozone formation, Terrestrial ecosystems	kg NOx eq	0,000351657	0,000312032	4,34846E-06	3,56032E-06	3,17164E-05
Terrestrial acidification	kg SO2 eq	0,000283059	0,00022162	8,85126E-06	2,69839E-06	4,98887E-05
Freshwater eutrophication	kg P eq	2,76782E-05	1,70315E-05	1,05702E-06	1,75188E-07	9,41449E-06
Marine eutrophication	kg N eq	5,27028E-06	3,9831E-06	7,19378E-08	2,05543E-08	1,19469E-06
Terrestrial ecotoxicity	kg 1,4-DCB	0,35296241	0,217241807	0,048314313	0,003631273	0,083775015
Freshwater ecotoxicity	kg 1,4-DCB	0,00778125	0,002582145	0,001379437	4,89638E-05	0,003770705
Marine ecotoxicity	kg 1,4-DCB	0,009849147	0,003430323	0,001691565	6,79195E-05	0,004659339
Human carcinogenic toxicity	kg 1,4-DCB	0,004005111	0,00257228	0,000399255	2,61202E-05	0,001007456
Human non-carcinogenic toxicity	kg 1,4-DCB	0,11111902	0,071773762	0,007016785	0,001849292	0,030479184
Land use	m2a crop eq	0,12256187	0,093738076	0,000780838	0,00042399	0,027618964
Mineral resource scarcity	kg Cu eq	0,000468436	0,00029262	0,000108936	3,35706E-06	6,35227E-05
Fossil resource scarcity	kg oil eq	0,019882734	0,014370523	0,000317338	0,000202223	0,00499265
Water consumption	m3	0,002375089	0,001627418	1,19153E-05	1,54092E-05	0,000720346

Product:	4,8 MJ Common busbar heat high temp (of project Biochar)						
Method:	ReCiPe 2016 Midpoint (H) V1.04 / World (2010) H						
Impact category	Unit	Total	Cooler heat	Gas flaring heat	Engine heat high temp	Heat pump heat	Flue exch.heat
Global warming	kg CO2 eq	0,01375934	0,00180398	0,00021974	0,00358889	0,00545506	0,002691669
Stratospheric ozone depletion	kg CFC11 eq	2,3982E-08	3,116E-09	3,2873E-10	5,971E-09	1,0088E-08	4,47828E-09
Ionizing radiation	kBq Co-60 eq	0,00045627	4,8582E-05	7,1287E-06	0,00010302	0,00022029	7,72613E-05
Ozone formation, Human health	kg NOx eq	0,00028321	8,7782E-06	9,5005E-07	0,00014527	1,9265E-05	0,000108951
Fine particulate matter formation	kg PM2.5 eq	4,5589E-05	2,8593E-06	4,0338E-07	2,0183E-05	7,0051E-06	1,51375E-05
Ozone formation, Terrestrial ecosystems	kg NOx eq	0,00028463	9,0024E-06	9,8361E-07	0,00014576	1,9556E-05	0,000109322
Terrestrial acidification	kg SO2 eq	0,000137	7,2463E-06	1,0938E-06	6,1417E-05	2,1176E-05	4,60631E-05
Freshwater eutrophication	kg P eq	6,4119E-06	7,0856E-07	5,8266E-08	1,4169E-06	3,1655E-06	1,06266E-06
Marine eutrophication	kg N eq	9,7972E-07	1,3492E-07	1,0312E-08	2,5976E-07	3,7992E-07	1,94817E-07
Terrestrial ecotoxicity	kg 1,4-DCB	0,0841399	0,00903584	0,00102134	0,01775897	0,04300451	0,01331923
Freshwater ecotoxicity	kg 1,4-DCB	0,00232157	0,0001992	1,533E-05	0,00039995	0,00140713	0,000299963
Marine ecotoxicity	kg 1,4-DCB	0,00290725	0,00025214	1,9804E-05	0,0005063	0,00174929	0,000379724
Human carcinogenic toxicity	kg 1,4-DCB	0,00084198	0,00010253	8,8848E-06	0,00021974	0,00034602	0,000164804
Human non-carcinogenic toxicity	kg 1,4-DCB	0,02652213	0,00284465	0,00023452	0,00591242	0,01309623	0,004434312
Land use	m2a crop eq	0,02264747	0,00313758	0,00022994	0,00606247	0,00867061	0,004546856
Mineral resource scarcity	kg Cu eq	8,9395E-05	1,1992E-05	9,9791E-07	2,6844E-05	2,9428E-05	2,01333E-05
Fossil resource scarcity	kg oil eq	0,00400592	0,000509	0,00016288	0,00102942	0,00153256	0,000772062
Water consumption	m3	0,0004721	6,0802E-05	4,4085E-06	0,00011095	0,00021273	8,32122E-05

Product:	2,82 MJ Engine electricity (of project Biochar)					
Method:	ReCiPe 2016 Midpoint (H) V1.04 / World (2010) H					
Impact category	Unit	Total	Washer syngas	CHP plant	Emissions	Lubricating oil {RER}| market for lubricating oil | APOS, U
Global warming	kg CO2 eq	0,03813198	0,03597457	0,00183809	0	0,000319326
Stratospheric ozone depletion	kg CFC11 eq	6,34E-08	6,21027E-08	1,05E-09	0	2,86E-10
Ionizing radiation	kBq Co-60 eq	0,00109454	0,000972091	8,26E-05	0	3,98E-05
Ozone formation, Human health	kg NOx eq	0,00154347	0,000174979	6,22E-06	0,00136039	1,88E-06
Fine particulate matter formation	kg PM2.5 eq	0,00021445	5,70135E-05	5,67E-06	0,00015115	6,11E-07
Ozone formation, Terrestrial ecosystems	kg NOx eq	0,00154873	0,000179448	6,37E-06	0,00136039	2,52E-06
Terrestrial acidification	kg SO2 eq	0,00065256	0,000144465	1,56E-05	0,00049081	1,64E-06
Freshwater eutrophication	kg P eq	1,51E-05	1,41276E-05	8,21E-07	0	1,06E-07
Marine eutrophication	kg N eq	2,76E-06	2,68937E-06	6,27E-08	0	7,81E-09
Terrestrial ecotoxicity	kg 1,4-DCB	0,18868909	0,1802449	0,00685134	0	0,001592862
Freshwater ecotoxicity	kg 1,4-DCB	0,00424948	0,003971837	0,00025583	0	2,18E-05
Marine ecotoxicity	kg 1,4-DCB	0,00537943	0,005027466	0,00032314	0	2,88E-05
Human carcinogenic toxicity	kg 1,4-DCB	0,00233472	0,002047424	0,00027516	0	1,21E-05
Human non-carcinogenic toxicity	kg 1,4-DCB	0,06281942	0,056723048	0,00570588	0	0,00039049
Land use	m2a crop eq	0,06441379	0,062527462	0,00167732	0	0,000209002
Mineral resource scarcity	kg Cu eq	0,00028522	0,000239501	4,29E-05	0	2,85E-06
Fossil resource scarcity	kg oil eq	0,01093755	0,01014742	0,00043772	0	0,000352414
Water consumption	m3	0,00117884	0,001165527	1,01E-05	0	3,20E-06

Product:	0,17 kg BC applied to soil (of project Biochar)						
Method:	ReCiPe 2016 Midpoint (H) V1.04 / World (2010) H						
Impact category	Unit	Total	BC transported to farm	Application to soil	Biochar	CO2 sequestration	N2O reduction
Global warming	kg CO2 eq	-0,27470517	0,00175398	0,000787628	0,02537523	-0,291	-0,011622
Stratospheric ozone depletion	kg CFC11 eq	-3,84E-07	1,20E-09	3,92E-10	4,38E-08	0	-4,29E-07
Ionizing radiation	kBq Co-60 eq	0,00076592	5,48E-05	2,23E-05	0,00068888	0	0
Ozone formation, Human health	kg NOx eq	0,00013511	4,92E-06	6,72E-06	0,00012346	0	0
Fine particulate matter formation	kg PM2.5 eq	4,40E-05	1,80E-06	1,98E-06	4,02E-05	0	0
Ozone formation, Terrestrial ecosystems	kg NOx eq	0,00013854	5,06E-06	6,86E-06	0,00012662	0	0
Terrestrial acidification	kg SO2 eq	0,00011005	4,28E-06	3,84E-06	0,00010193	0	0
Freshwater eutrophication	kg P eq	1,03E-05	1,80E-07	1,68E-07	9,97E-06	0	0
Marine eutrophication	kg N eq	1,93E-06	1,82E-08	1,57E-08	1,90E-06	0	0
Terrestrial ecotoxicity	kg 1,4-DCB	0,15104968	0,02045937	0,003492375	0,12709793	0	0
Freshwater ecotoxicity	kg 1,4-DCB	0,00291287	6,27E-05	4,84E-05	0,0028018	0	0
Marine ecotoxicity	kg 1,4-DCB	0,00370267	9,35E-05	6,27E-05	0,00354642	0	0
Human carcinogenic toxicity	kg 1,4-DCB	0,00153877	5,63E-05	3,85E-05	0,00144399	0	0
Human non-carcinogenic toxicity	kg 1,4-DCB	0,04373122	0,00172617	0,001990407	0,04001464	0	0
Land use	m2a crop eq	0,04456074	0,00024099	0,000195317	0,04412443	0	0
Mineral resource scarcity	kg Cu eq	0,00019347	1,05E-05	1,42E-05	0,00016877	0	0
Fossil resource scarcity	kg oil eq	0,00795882	0,00057989	0,00021946	0,00715947	0	0
Water consumption	m3	0,00092247	4,10E-06	3,06E-06	0,00091531	0	0

Results on endpoint impact categories

Product:	1 p Gasification (of project Biochar)	
Method:	ReCiPe 2016 Endpoint (H) V1.04 / World (2010) H/A	
Impact category	Unit	Biomass & Gasification
Global warming, Human health	DALY	6,54E-08
Global warming, Terrestrial ecosystems	species.yr	1,97E-10
Global warming, Freshwater ecosystems	species.yr	5,39E-15
Stratospheric ozone depletion	DALY	6,46E-11
Ionizing radiation	DALY	1,61E-11
Ozone formation, Human health	DALY	3,12E-10
Fine particulate matter formation	DALY	7,02E-08
Ozone formation, Terrestrial ecosystems	species.yr	4,54E-11
Terrestrial acidification	species.yr	6,00E-11
Freshwater eutrophication	species.yr	1,85E-11
Marine eutrophication	species.yr	8,95E-15
Terrestrial ecotoxicity	species.yr	4,03E-12
Freshwater ecotoxicity	species.yr	5,38E-12
Marine ecotoxicity	species.yr	1,04E-12
Human carcinogenic toxicity	DALY	1,33E-08
Human non-carcinogenic toxicity	DALY	2,53E-08
Land use	species.yr	1,09E-09
Mineral resource scarcity	USD2013	0,00010829
Fossil resource scarcity	USD2013	0,00752375
Water consumption, Human health	DALY	4,03E-09
Water consumption, Terrestrial ecosystem	species.yr	2,62E-11
Water consumption, Aquatic ecosystems	species.yr	1,64E-15

Product:	4,47 MJ Common busbar heat high temp with heating grid (of project Biochar)			
Method:	ReCiPe 2016 Endpoint (H) V1.04 / World (2010) H/A			
Impact category	Unit	Total	Common busbar heat high temp	Heating grid
Global warming, Human health	DALY	1,58E-08	1,19E-08	3,86E-09
Global warming, Terrestrial ecosystems	species.yr	4,75E-11	3,59E-11	1,17E-11
Global warming, Freshwater ecosystems	species.yr	1,30E-15	9,80E-16	3,18E-16
Stratospheric ozone depletion	DALY	1,38E-11	1,19E-11	1,92E-12
Ionizing radiation	DALY	4,98E-12	3,61E-12	1,37E-12
Ozone formation, Human health	DALY	2,51E-10	2,40E-10	1,10E-11
Fine particulate matter formation	DALY	3,32E-08	2,67E-08	6,50E-09
Ozone formation, Terrestrial ecosystems	species.yr	3,58E-11	3,41E-11	1,62E-12
Terrestrial acidification	species.yr	3,11E-11	2,70E-11	4,07E-12
Freshwater eutrophication	species.yr	4,81E-12	4,00E-12	8,11E-13
Marine eutrophication	species.yr	1,89E-15	1,55E-15	3,35E-16
Terrestrial ecotoxicity	species.yr	1,50E-12	8,94E-13	6,04E-13
Freshwater ecotoxicity	species.yr	1,62E-12	1,50E-12	1,28E-13
Marine ecotoxicity	species.yr	3,12E-13	2,85E-13	2,75E-14
Human carcinogenic toxicity	DALY	4,88E-09	2,60E-09	2,27E-09
Human non-carcinogenic toxicity	DALY	6,65E-09	5,63E-09	1,01E-09
Land use	species.yr	1,96E-10	1,87E-10	8,42E-12
Mineral resource scarcity	USD2013	5,91E-05	1,92E-05	3,98E-05
Fossil resource scarcity	USD2013	0,00185129	0,00131651	0,00053478
Water consumption, Human health	DALY	7,33E-10	6,78E-10	5,54E-11
Water consumption, Terrestrial ecosystem	species.yr	4,78E-12	4,43E-12	3,55E-13
Water consumption, Aquatic ecosystems	species.yr	3,06E-16	2,75E-16	3,06E-17

Product:	2,82 MJ Electricity_output (of project Biochar)		
Method:	ReCiPe 2016 Endpoint (H) V1.04 / World (2010) H/A		
Impact category	Unit	Total	Engine electricity
Global warming, Human health	DALY	3,54E-08	3,54E-08
Global warming, Terrestrial ecosystems	species.yr	1,07E-10	1,07E-10
Global warming, Freshwater ecosystems	species.yr	2,92E-15	2,92E-15
Stratospheric ozone depletion	DALY	3,37E-11	3,37E-11
Ionizing radiation	DALY	9,29E-12	9,29E-12
Ozone formation, Human health	DALY	1,40E-09	1,40E-09
Fine particulate matter formation	DALY	1,35E-07	1,35E-07
Ozone formation, Terrestrial ecosystems	species.yr	1,99E-10	1,99E-10
Terrestrial acidification	species.yr	1,38E-10	1,38E-10
Freshwater eutrophication	species.yr	1,01E-11	1,01E-11
Marine eutrophication	species.yr	4,69E-15	4,69E-15
Terrestrial ecotoxicity	species.yr	2,15E-12	2,15E-12
Freshwater ecotoxicity	species.yr	2,94E-12	2,94E-12
Marine ecotoxicity	species.yr	5,66E-13	5,66E-13
Human carcinogenic toxicity	DALY	7,75E-09	7,75E-09
Human non-carcinogenic toxicity	DALY	1,43E-08	1,43E-08
Land use	species.yr	5,72E-10	5,72E-10
Mineral resource scarcity	USD2013	6,59E-05	6,59E-05
Fossil resource scarcity	USD2013	0,00408419	0,00408419
Water consumption, Human health	DALY	2,07E-09	2,07E-09
Water consumption, Terrestrial ecosystem	species.yr	1,34E-11	1,34E-11
Water consumption, Aquatic ecosystems	species.yr	8,52E-16	8,52E-16

Product:	0,17 kg BC applied to soil (of project Biochar)						
Method:	ReCiPe 2016 Endpoint (H) V1.04 / World (2010) H/A						
Impact category	Unit	Total	BC transported	Application to soil	Biochar	CO2 sequestration	N2O reduction
Global warming, Human health	DALY	-2,55E-07	1,63E-09	7,31E-10	2,36E-08	-2,70E-07	-1,08E-08
Global warming, Terrestrial ecosystems	species.yr	-7,69E-10	4,91E-12	2,21E-12	7,11E-11	-8,15E-10	-3,25E-11
Global warming, Freshwater ecosystems	species.yr	-2,10E-14	1,34E-16	6,02E-17	1,94E-15	-2,23E-14	-8,89E-16
Stratospheric ozone depletion	DALY	-2,04E-10	6,38E-13	2,08E-13	2,33E-11	0	-2,28E-10
Ionizing radiation	DALY	6,50E-12	4,65E-13	1,89E-13	5,85E-12	0	0
Ozone formation, Human health	DALY	1,23E-10	4,48E-12	6,12E-12	1,12E-10	0	0
Fine particulate matter formation	DALY	2,77E-08	1,13E-09	1,24E-09	2,53E-08	0	0
Ozone formation, Terrestrial ecosystems	species.yr	1,79E-11	6,53E-13	8,85E-13	1,63E-11	0	0
Terrestrial acidification	species.yr	2,33E-11	9,07E-13	8,14E-13	2,16E-11	0	0
Freshwater eutrophication	species.yr	6,91E-12	1,21E-13	1,13E-13	6,68E-12	0	0
Marine eutrophication	species.yr	3,28E-15	3,10E-17	2,66E-17	3,22E-15	0	0
Terrestrial ecotoxicity	species.yr	1,72E-12	2,33E-13	3,99E-14	1,45E-12	0	0
Freshwater ecotoxicity	species.yr	2,01E-12	4,34E-14	3,35E-14	1,94E-12	0	0
Marine ecotoxicity	species.yr	3,89E-13	9,83E-15	6,59E-15	3,73E-13	0	0
Human carcinogenic toxicity	DALY	5,11E-09	1,87E-10	1,28E-10	4,79E-09	0	0
Human non-carcinogenic toxicity	DALY	9,97E-09	3,94E-10	4,54E-10	9,13E-09	0	0
Land use	species.yr	3,96E-10	2,14E-12	1,73E-12	3,92E-10	0	0
Mineral resource scarcity	USD2013	4,47E-05	2,42E-06	3,29E-06	3,90E-05	0	0
Fossil resource scarcity	USD2013	0,00303666	0,00024545	8,23E-05	0,00270895	0	0
Water consumption, Human health	DALY	1,46E-09	4,09E-12	2,02E-12	1,45E-09	0	0
Water consumption, Terrestrial ecosystem	species.yr	9,51E-12	2,82E-14	1,70E-14	9,47E-12	0	0
Water consumption, Aquatic ecosystems	species.yr	5,98E-16	3,19E-18	2,89E-18	5,92E-16	0	0

Economic and energy allocation

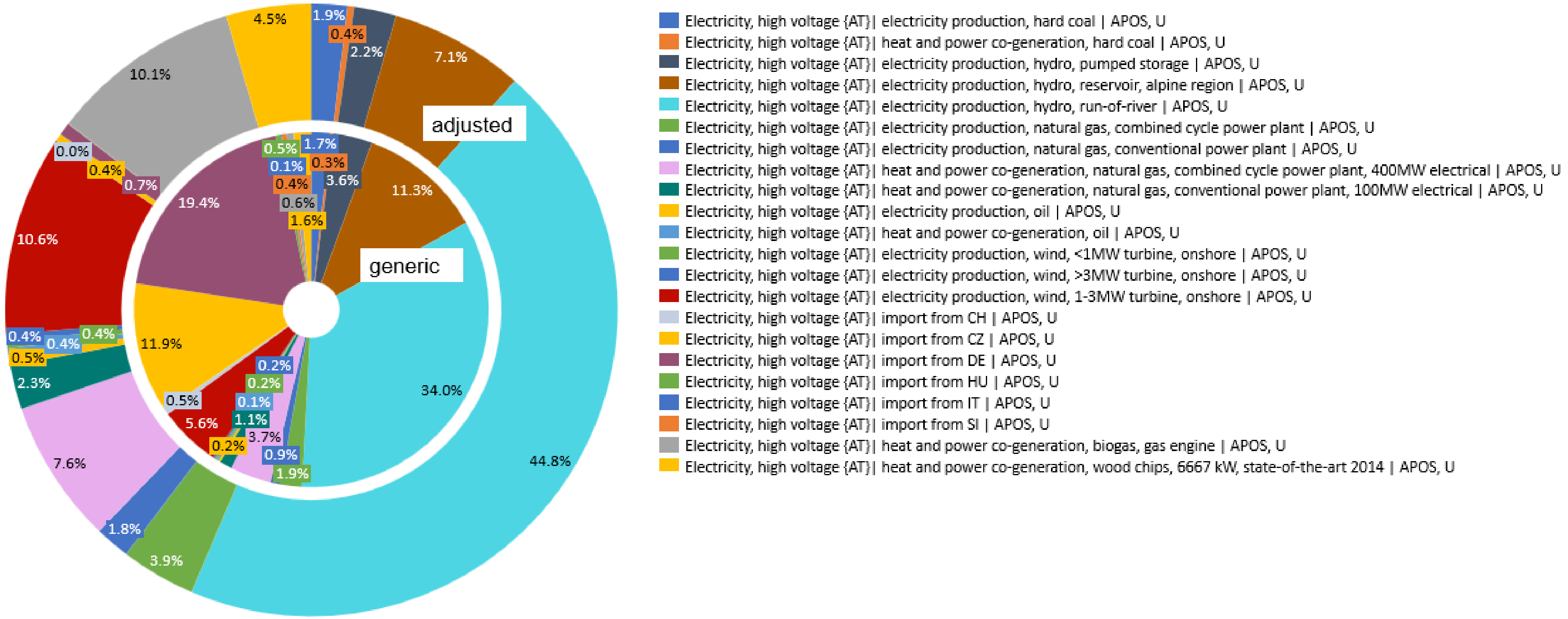
		Economic allocation				Energy allocation		
Process	**Product**	**Amount**	**Market price[4]*Amount**	**Economic Allocation result**		**Amount**	**Energy Allocation result**	
Gasification	Electricity	1.765.393 kWh	370.733 €	**51%**	**64%**	1.765.393 kWh	**22%**	**60%**
	Heat	3.008.262 kWh	90.248 €	**12%**		3.008.262 kWh	**38%**	
	Biochar	377 tons	263.816 €	**36%**		3.140.667 kWh	**40%**	
	∑		724.796 €			7.914.322 kWh		
Cooler	Cooler syngas	1.765.393 kWh	370.733 €	**80%**	**96%**	1.765.393 kWh	**37%**	**86%**
		2.346.352	70.391 €	**15%**		2.346.352 kWh	**49%**	
	Cooler heat	661.910 kWh	19.857 €	**4%**		661.910 kWh	**14%**	
	∑	∑	460.980 €			4.773.655 kWh		
Washer	Washer syngas	1.765.393 kWh	370.733 €	**84%**	**98.7%**	1.765.393 kWh	**43%**	**94%**
		2.103.700 kWh	63.111 €	**14%**		2.103.700 kWh	**51%**	
	Washer heat	188.260 kWh	4.518 €	**1%**		188.260 kWh	**5%**	
	Washer syngas to gas flaring	54.392 kWh	1.305 €	**0.3%**		54.392 kWh	**1%**	
	∑	∑	439.667 €			4.111.745 kWh		
Engine	Engine electricity	1.765.393 kWh	370.733 €	**85%**		1.765.393 kWh	**44%**	
	Engine heat high temp	1.222.980 kWh	36.689 €	**8%**		1.222.980 kWh	**31%**	
	Engine flue gases	kWh	25.295 €	**6%**		843.170 kWh	**21%**	
	Engine heat low temp	147.950 kWh	3.551 €	**1%**		147.950 kWh	**4%**	
	∑		436.268 €			3.979.493 kWh		

[4] Market prices: Electricity: 0.21€/kWh; Heat: 0.03€/kWh; Biochar: 700€/t

Adjusted electricity mix

Electricity/heat	Value generic	Unit	Value adjusted	Unit
Electricity, high voltage {AT}| electricity production, hard coal | APOS, U	0,016756	kWh	0,01686252772	kWh
Electricity, high voltage {AT}| heat and power co-generation, hard coal | APOS, U	0,003118	kWh	0,00313747228	kWh
Electricity, high voltage {AT}| electricity production, hydro, pumped storage | APOS, U	0,04	kWh	0,01985347839	kWh
Electricity, high voltage {AT}| electricity production, hydro, reservoir, alpine region | APOS, U	0,11	kWh	0,06333966345	kWh
Electricity, high voltage {AT}| electricity production, hydro, run-of-river | APOS, U	0,34	kWh	0,40000000000	kWh
Electricity, high voltage {AT}| electricity production, natural gas, combined cycle power plant | APOS, U	0,02	kWh	0,03510686765	kWh
Electricity, high voltage {AT}| electricity production, natural gas, conventional power plant | APOS, U	0,01	kWh	0,01645634420	kWh
Electricity, high voltage {AT}| heat and power co-generation, natural gas, combined cycle power plant, 400MW electrical | APOS, U	0,04	kWh	0,06777250727	kWh
Electricity, high voltage {AT}| heat and power co-generation, natural gas, conventional power plant, 100MW electrical | APOS, U	0,01	kWh	0,02066428089	kWh
Electricity, high voltage {AT}| electricity production, oil | APOS, U	0,00209317	kWh	0,00467692308	kWh
Electricity, high voltage {AT}| heat and power co-generation, oil | APOS, U	0,00148725	kWh	0,00332307692	kWh
Electricity, high voltage {AT}| electricity production, wind, <1MW turbine, onshore | APOS, U	0,00	kWh	0,00339584977	kWh
Electricity, high voltage {AT}| electricity production, wind, >3MW turbine, onshore | APOS, U	0,00	kWh	0,00334278962	kWh
Electricity, high voltage {AT}| electricity production, wind, 1-3MW turbine, onshore | APOS, U	0,06	kWh	0,09426136060	kWh
Electricity, high voltage {AT}| import from CH | APOS, U	0,00	kWh	0,00013851645	kWh
Electricity, high voltage {AT}| import from CZ | APOS, U	0,12	kWh	0,00364227238	kWh
Electricity, high voltage {AT}| import from DE | APOS, U	0,19	kWh	0,00591269912	kWh
Electricity, high voltage {AT}| import from HU | APOS, U	0,01	kWh	0,00015307844	kWh
Electricity, high voltage {AT}| import from IT | APOS, U	0,00	kWh	0,00002379642	kWh
Electricity, high voltage {AT}| import from SI | APOS, U	0,00	kWh	0,00012963719	kWh
Electricity, high voltage {AT}| heat and power co-generation, biogas, gas engine | APOS, U	0,01	kWh	0,09000000000	kWh
Electricity, high voltage {AT}| heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014 | APOS, U	0,02	kWh	0,04000000000	kWh
Electricity, high voltage {AT}| market for | APOS, U	0,02	kWh	0,89219314184	kWh

Electricity mix graphical overview



Constructions

Storage bunker	Value	Unit
Products		
storage bunker	1	p
Resources		
Gravel	798	ton
Occupation, grassland	27000	m2a
Transformation, from grassland	900	m2
Materials/fuels		
Excavation, hydraulic digger {RER}| processing | APOS, U	558	m3
Transport, freight, lorry 3.5-7.5 metric ton, euro6 {RER}| market for transport, freight, lorry 3.5-7.5 metric ton, EURO6 | APOS, U	39938	tkm
Concrete, sole plate and foundation {CH}| market for | APOS, U	108	m3
Concrete, normal {CH}| market for | APOS, U	56	m3
Reinforcing steel {GLO}| market for | APOS, U	16800	kg
Sawnwood, softwood, dried (u=20%), planed {RER}| market for | APOS, U	76	m3
Steel, low-alloyed, hot rolled {GLO}| market for | APOS, U	14,68	kg
Steel, chromium steel 18/8, hot rolled {GLO}| market for | APOS, U	300	kg
Machine operation, diesel, < 18.64 kW, generators {GLO}| market for | APOS, U	250	hr
Electricity, high voltage {AT}| electricity production, hydro, run-of-river | APOS, U	500	kWh
Waste to treatment		
Waste concrete {Europe without Switzerland}| market for waste concrete | APOS, U	404	ton
Waste building wood, chrome preserved {CH}| market for | APOS, U	26,6	ton
Scrap steel {Europe without Switzerland}| market for scrap steel | APOS, U	16,8	ton

Main building	Value	Unit
Products		
main building	1	p
Resources		
Sand and gravel	700	kg
Occupation, industrial area	6510	m2a
Transformation, from industrial area	217	m2
Materials/fuels		
Excavation, hydraulic digger {RER}| processing | APOS, U	480	m3
Transport, freight, lorry 7.5-16 metric ton, euro6 {RER}| market for transport, freight, lorry 7.5-16 metric ton, EURO6 | APOS, U	13920	tkm
Concrete, sole plate and foundation {CH}| market for | APOS, U	312	m3
Sawnwood, softwood, raw, dried (u=10%) {RER}| market for | APOS, U	18	m3
Flat glass, uncoated {RER}| market for flat glass, uncoated | APOS, U	850	kg
Bitumen seal {GLO}| market for | APOS, U	1500	kg
Polystyrene foam slab {GLO}| market for | APOS, U	1050	kg
Machine operation, diesel, < 18.64 kW, generators {GLO}| machine operation, diesel, < 18.64 kW, generators | APOS, U	1250	hr
Electricity, high voltage {AT}| electricity production, hydro, run-of-river | APOS, U	7500	kWh
Waste to treatment		
Waste cement in concrete and mortar {Europe without Switzerland}| market for waste cement in concrete and mortar | APOS, U	748,8	ton
Waste wood, untreated {AT}| market for waste wood, untreated | APOS, U	6,3	ton
Waste polystyrene {AT}| market for waste polystyrene | APOS, U	1050	kg
Waste bitumen sheet {CH}| market for | APOS, U	1500	kg
Waste glass {AT}| market for waste glass | APOS, U	850	kg

Gasification system	Value	Unit
Products		
gasification system	1	p
Materials/fuels		
Steel, chromium steel 18/8, hot rolled {GLO}| market for | APOS, U	7,2	ton
Steel, unalloyed {GLO}| market for | APOS, U	9,6	ton
Aluminium, cast alloy {GLO}| market for | APOS, U	350	kg
Copper {GLO}| market for | APOS, U	350	kg
Stone wool {GLO}| market for stone wool | APOS, U	3	ton
Ceramic tile {GLO}| market for | APOS, U	84	kg
Energy requirement for assembly of heat and power co-generation unit, 160kW electrical {RER}| energy requirement for assembly of heat and power co-generation unit, 160kW electrical | APOS, U	1	p
Waste to treatment		
Scrap aluminium {Europe without Switzerland}| market for scrap aluminium | APOS, U	350	kg
Scrap copper {Europe without Switzerland}| market for scrap copper | APOS, U	350	kg
Scrap steel {Europe without Switzerland}| market for scrap steel | APOS, U	16,8	ton
Inert waste {Europe without Switzerland}| market for inert waste | APOS, U	3048	kg

CHP plant	Value	Unit
Products		
CHP plant	1	p
Materials/fuels		
Air input/output unit, heat and power co-generation unit, 160kW electrical {GLO}| market for | APOS, U	1	p
Gas motor, 206kW {GLO}| market for | APOS, U	1	p
Control cabinet, heat and power co-generation unit, 160kW electrical {GLO}| market for | APOS, U	1	p
Sound insulation, heat and power co-generation unit, 160kW electrical {GLO}| market for | APOS, U	1	p
Catalytic converter, three-way, 19.1l {GLO}| market for | APOS, U	1	p
Energy requirement for assembly of heat and power co-generation unit, 160kW electrical {GLO}| market for | APOS, U	1	p
Waste to treatment		
Waste polyethylene {AT}| market for waste polyethylene | APOS, U	78,5	kg
Scrap copper {Europe without Switzerland}| market for scrap copper | APOS, U	10,8	kg
Scrap steel {Europe without Switzerland}| market for scrap steel | APOS, U	2681,5	kg
Inert waste, for final disposal {CH}| market for inert waste, for final disposal | APOS, U	480	kg

Heating grid 1m	Value	Unit
Products		
Heat grid 1m	1	m
Resources		
Sand and gravel	1175	kg
Occupation, grassland, natural (non-use)	50	m2a
Transformation, from grassland, natural (non-use)	1,25	m2
Materials/fuels		
Excavation, hydraulic digger {RER}| processing | APOS, U	1,2	m3
Transport, freight, lorry 7.5-16 metric ton, euro5 {RoW}| market for transport, freight, lorry 7.5-16 metric ton, EURO5 | APOS, U	38,77	tkm
Mastic asphalt {GLO}| market for | APOS, U	197,16	kg
Chromium steel pipe {GLO}| market for | APOS, U	8,75	kg
Polyethylene, high density, granulate {RER}| production | APOS, U	2,52	kg
Polyurethane, rigid foam {RER}| market for polyurethane, rigid foam | APOS, U	1,72	kg
Machine operation, diesel, < 18.64 kW, generators {GLO}| market for | APOS, U	0,11	hr
Heating grid 1p	Value	Unit
Products		
Heating Network	1	p
Materials/fuels		
Heat grid 1m	3070,3	m